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Visualization of River Water Flow in Hydrodynamically Active Areas under Different Flow Regimes

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ABSTRACT

It was established that in the territory of the Stryi river basin, the natural landscapes are maximally preserved in comparison with other regions of Western Ukraine, but under modern conditions an increase of negative anthropogenic impact on the quality of natural waters is observed. The hydrodynamic barriers or hydrodynamically active areas (HAA) of mountain rivers, characterized by a significant oxygen saturation of the water flow, which activates the processes of biochemical and biological self-purification of surface waters, are important for the efficiency of self-purification processes. In order to verify the results of theoretical and field research, an existing experimental setup was designed and improved. It provided the conditions for modeling the flow of mountain rivers in accordance with the laws of similarity theory and the principles of hydrodynamic modeling. On the basis of the results of field observations in the foothills of rivers, as well as regulatory and design documentation, the limits of the main operating factors were determined, namely the Freud number, flow depth and flow rate, which are decisive in studying the impact of HAA on flow self-cleaning processes. By changing the length of the tray section, the gullies and the waterfall niche of the real hydrodynamically active section were simulated, on which field experiments on the Tyshivnytsia River were conducted. In the studies, measurements were performed at different flow regimes, which simulated different hydrological parameters. In order to analyze the impact of HAA on self-cleaning processes, the flow was visualized using photography. The change in the structure of a stream of natural waters at passage of HAA was established. The high oxygen saturation of the river waters of the Stryi river basin is caused by the influence of HAA, which contribute to the purification of polluted waters from biological pollutants and other man-made pollutants and form the high quality of water resources in the region. A method of modeling and visualization of mountain rivers in the laboratory was developed.

Keywords: mountain rivers, self-cleaning processes, surface waters, hydrodynamically active areas, flow visualization, cavitation phenomena.

INTRODUCTION

Self-purification of natural watercourses occurs under the influence of extremely different factors acting simultaneously in different combinations, namely: a) hydraulic – dilution and mixing of pollutants with the bulk of water; b) mechanical – deposition of suspended particles; c) physical – the effects of solar radiation and temperature; d) chemical – oxidation of organic and mineral pollutants; e) biological – flora and fauna, which participates in the process of natural self-purification.

In the territory of the Stryi river basin, the natural landscapes are maximally preserved in comparison with other regions of Western Ukraine, but under modern conditions, an increase in the negative anthropogenic impact on the quality of natural waters is observed. The hydrodynamic barriers or hydrodynamically active sections of mountain rivers, characterized by a significant oxygen saturation of the water flow, which activates the processes of biochemical and biological self-purification of natural waters, are important for increasing the efficiency of self-purification processes.

The hydrodynamically active area (HAA) is understood as a local natural or artificial obstacle in the course of water flow, namely waterfalls, rapids, gullies, waterfalls, boulders and their cascades. When passing through them, the watercourse is disturbed, the transition from laminar to turbulent flow with the activation of cavitation phenomena, which causes a sharp increase in the speed of movement of the water mass, its splashing and foaming. As a result of these processes there is a maximum saturation of water with dissolved oxygen with the effect of biological treatment of "natural treatment plant", which is accompanied by the phenomenon of short-term change of clear and colorless water to opaque and white fluid [Borutska, 2015].

N.I. Makkaveev was one of the first to investigate the presence of cavitation phenomena in the channels of mountain rivers [Borutska, 2015; Chalov, 2002]. On the slope of the river, he distinguished calm with laminar and turbulent with turbulent flow water flows. Calm are characterized by slight deviations of the surface marks over individual obstacles (boulders, ridges), their flow without disturbing the continuity of the flow due to low flow velocities, as well as without visually noticeable losses of potential energy. The turbulent flow forms a standing wave over the obstacles, which is caused by the loss of energy in the collision with the obstacle, when the potential energy of the flow becomes kinetic. The movement of the calm flow solely due to the potential energy leads to a decrease in the depth of the channel, its siltation and lowering the level. In a turbulent flow, due to the kinetic energy, the depth of the channel increases, but the speed decreases after meeting an obstacle. The stream flows around the steep curves of the shores, without forming stagnant zones and eddies. If a vortex is formed in the turbulent flow due to a sharp decrease in pressure, the phenomenon of hydrodynamic cavitation is observed, which causes cavitation erosion and more active interaction with atmospheric air.

The factors that affect calm and turbulent flows, as well as turbulent with the phenomena of hydrodynamic cavitation are the value of the critical slope of the channel, i.e. I_{cr} and the parameter of flow kinetics. Given the different roughness of the bottom, the Reynolds number ranges from 300 (very rough) to 3000 (perfectly smooth). For the parameter of the kinetics of the flow using the Freud number, which is calculated by the formula $Fr = V^2 / gh$, where h is the depth of the flow, m. The condition of a calm flow is $I < I_{cr}$ and $Fr < 1$, and the condition of a rapid flow is $I > I_{cr}$ and $Fr > 1$ [Snitynskyi et al., 2020]. For a turbulent flow with the phenomena of hydrodynamic cavitation, the criteria are $I >> I_{cr}$ and $Fr >> 1$, which lead to the formation of vortices in the case of overcoming obstacles.

The areas of perturbation and activation of cavitation phenomena lead to a sharp increase in the speed of water mass as well as its splashing and are accompanied by a short-term change in the transparency and color of water, with the formation of opaque fluid in mountain river basins. It is formed only where the bedrock in the channels is sufficiently resistant to water erosion, and the underlying layers are much easier to denudate, where a water niche is formed [Borutska, 2015; Snitynskyi et al., 2020]. The place of falling of water gradually shifts or the water stream quickly flows down from surfaces of differences, forming a system of large and small waterfalls which are called cascades. Sometimes, the water destroys the cliff so much that it washes the bed in it, begins to fall not vertically, but slides down a rocky gutter forming waterfalls. Often, waterfalls form a complex system of waterfalls and cascades. Most of the waterfalls in the basin of the Stryi River are located at the intersections of watercourses and exits to the outer surface of the most resistant to water erosion massive sandstones.

The hydraulics of mountain streams are characterized by shallow turbulent currents and high relative roughness caused by protruding boulders, rocks and remnants of wood washed from the slopes. Scientific publications [Reid and Hickin, 2008; Chiari and Rickenmann, 2011] show that, in contrast to rivers with a smaller gradient, these significant elements of roughness account for up to 80–90 percent of the total roughness of the rapid flow of mountain rivers. The flow velocity varies over relatively short longitudinal distances due to the unevenness of morphological elements and the presence of thresholds and differences.

The largest variations are observed in the stepped channel, where supercritical flows are mainly formed from stepped ridges to points of impact [Comiti et al., 2007]. The flow resistance of mountain rivers varies considerably, depending on the depth of the flow compared to large rivers. Reid and Hikin [Reid and Hickin, 2008] demonstrated more than six orders of magnitude of the Darcy – Weisbach resistance coefficient for the average depth range, which ranged from 20 to 36 cm. They also pointed out the difficulties in estimating the average depth of flow in shallow waters with large roughness elements. The monograph [Radecki-Pawlik et al., 2018] states that geomorphological processes, channel morphology and hydraulics of mountain streams, significantly differ from the typical gravel bed or winding rivers.

In waterfalls, a free space is often formed between the flow of free-falling water to the waterfall niche and the rock outcrop, the reason for the formation of which is the phenomena of hydrodynamic cavitation and cavitation erosion. The predominance of pebble, boulder and block sediments in the riverbed causes great roughness of the bottom, creates significant obstacles in the way of water flow and contributes to cavitation phenomena. In the case of very large slopes of mountain rivers, rapids are formed, the morphological appearance of which is determined by boulders and lump of different sizes, as well as existing waterfalls. Slope ranges for different mountain rivers are not the same and hydrodynamic barriers are located only in certain places, which are called areas of cavitation water treatment and oxygen saturation [Borutska, 2015].

Cavitation is understood as the rupture of the continuity of the aquatic environment due to local pressure reduction, which may be hydrodynamic or acoustic in nature [Young, 1999]. Hydrodynamic cavitation occurs due to an increase in flow velocity, which leads to the formation of microbubbles, which briefly change the color of water in the flow, while acoustic to the appearance of acoustic waves, sound effect (noise, roar of water flow). Acoustic cavitation occurs when acoustic, and especially ultrasonic waves are exposed to water. In the Stryi river basin, exclusively hydrodynamic cavitation is observed, which occurs in the areas where the pressure drops to a critical value, when the flow enters the zone of "liquid continuity rupture" and microbubbles are generated, and further movement leads to unlimited growth of microbubbles [Snitynskyi et al., 2020].

Air-water flows have recently been studied in comparison with classical fluid mechanics. Although some researchers (such as Leonardo da Vinci) have observed free surface aeration and discussed the possible effects, the first successful experimental studies were conducted in the mid-20th century by Ehrenberger [1926] in Austria and Straub and Anderson [1958] in North America. Another stage was a series of experimental studies conducted at the catchment area of the Avimor Dam in New Zealand under the leadership of I.R. Wood [Cain, and Wood, 1981], which showed the complexity of the process of aeration of the free surface. Scientists have developed the basic principles of modern calculations of self-aerated flow and shown examples of interfacial aeration with the formation of "white water" down the mountain stream [Wood, 1991].

The photos of the Avimor Dam spillway showed that the air is captured by the action of many irregular vortices operating near the free surface. The capture of air bubbles is mainly caused by fluctuations in the turbulence that acts near the free surface of the water. Through the "free surface" the air is constantly delayed and released. Air bubbles can be captured when the turbulent kinetic energy is large enough to overcome both surface tension and gravity [Chanson, 2004].

The purpose of the work was to determine the influence of hydrodynamically active areas (HAA) of mountain rivers on the processes of natural self-purification and to develop the methods of laboratory modeling of these areas to determine the hydrochemical parameters of river waters.

In order to achieve this goal, the following tasks were set:

- to determine the change in the structure of the flow of natural waters during the passage of HAA and its impact on the processes of natural self-purification;
- to develop a method of modeling and visualization of mountain rivers in the laboratory.

MATERIALS AND METHODS

The methods of research of ecological and hydrochemical factors of formation of chemical composition of natural waters of the Stryi river basin combine basin and landscape-geochemical approaches. It allows integrating a variety of natural and anthropogenic impacts and identifying the most important parameters for their detailed analysis. The combination of these approaches made it possible to improve the method of ecological analysis of the area of the Stryi river basin, which allows spatially differentiating and hydrochemically integrating the factors of formation of the chemical composition of natural waters.

In order to verify the results of theoretical and field research, an existing experimental setup was designed and improved, which provided conditions for modeling the flow of mountain rivers in accordance with the laws of similarity theory and the principles of hydrodynamic modeling [Voznyak et al., 2019]. On the basis of the results of field observations in the foothills of rivers, as well as regulatory and design documentation, the limits of the main operating factors were determined, namely the Freud number, flow depth and flow rate, which are decisive in studying the impact of HAA on flow self-cleaning processes.

The criterion of dynamic similarity was Freud's criterion as the main one for hydrodynamic similarity with the predominance of gravity [Krutov et al., 1989]. Taking into account the peculiarities of hydrodynamic modeling according to the Freud test, as well as the characteristic features of natural surface flows, it was decided to change the vertical geometric scale of the model ($C_H \neq C_L$). In addition, for modeling surface flows of insignificant depth, it was allowed to change the horizontal and vertical scales so that the ratio of width and depth of the flow in the model was not less than 6 [Krutov et al., 1989], and the scale discrepancy should be limited by the condition R ≈ h. The experimental model of HAA mountain stream fully meets these requirements.

The next condition for correct modeling is the kinematic similarity of the flows, i.e. the similarity of the average velocities in the corresponding cross sections of the flow. Hydraulic slopes and surface roughness coefficients of the model flow were taken in kind, i.e. $I_m = I_n$, $n_{1.m} = n_{1.n}$. Therefore, it was assumed that the depths of the flows of the model and full-scale channels in the respective sections should be the same, namely $C_H = 1$. The Freud number for open flows $Fr = V^2/gH$, so for similarity according to the Freud criterion ($Fr_n = Fr_m$) speed scale $C_v = C_H^{1/2} = 1$.

The second condition for modeling hydraulic phenomena is the similarity of the flow regime. Since the corresponding depths of natural and model flows were assumed to be the same, and the hydraulic radius for shallow broad flows R = h, the same values of the average flow velocity and kinematic viscosity of the fluid automatically fulfill the condition of equality in nature and on the Reynolds test model ($Re_n = Re_m$).

$$\text{Re} = VR/v \quad (1)$$

$$C_{\text{Re}} = \frac{C_V C_H}{C_v} = 1 \quad (2)$$

Thus, at the same time, the similarity of full-scale and modulated flows according to the criteria of Freud and Reynolds is provided.

Water flow Q was measured by a triangular spillway with a right angle near the vertex and determined by the formula of H. King [SNiP 2.01.14-83, 1985]

$$\text{Q} = 1.343\text{H}^{2.47},\ m^3/s \quad (3)$$

where: H is the pressure at the threshold of the spillway, i.e. above the top of the right angle, m.

Experimental hydrochemical studies were performed in the laboratory of the Department of Hydraulic Engineering and Water Engineering of the National University "Lviv Polytechnic" on a small hydraulic tray (Fig. 1). The total length of the tray is 9.6 m, width equals 0.23 m, and the height of the side walls amounts to 0.34 m. The tray consists of two sections. The first section is 6.53 m long with zero bottom slope, and the second section has a height difference of 0.26 m and a length of 3.07 m, which allows modeling the flow through the waterfall. The side walls of the tray are made of glass. At the end of the tray there is a metal gate valve to adjust the depth of flow. Water from the tray flowed into the measuring tank, and from there into the receiving tank (Figs. 2, 3).

Water was supplied to the tray via a 13.6 m^3 pressure tank located on the sixth floor of the laboratory building. This provided a working pressure on the experimental tray of about 20 m of water column. Water flow Q was controlled by a valve and measured by a flow tank containing a triangular spillway. After the spillway, the water passed through a system of flow permeation dampers, which ensured a uniform flow of water into the tray. Measurement of the pressure and water levels was performed using a micrometer-level meter 7. In order to determine the water flow used a standardized thin-walled spillway 5.

By varying the size of the rocks, the depth of the flow and the length of the area where the field studies were conducted, the flow through the real hydrodynamically active area was modeled, including the gullies and the waterfall niche of the waterfall (Fig. 4).

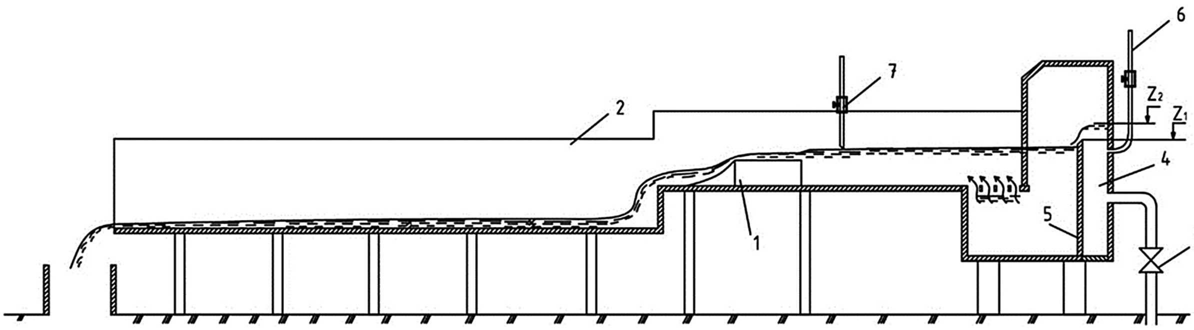


Figure 1. Scheme of the laboratory stand (longitudinal section): 1 – experimental spillway with a wide threshold; 2 – hydraulic tray; 3 – latch on the water supply pipeline to the tray; 4 – water meter unit; 5 – spillway "thin wall"; 6 – piezometric tube complete with micrometer - level gauge; 7 – mobile micrometer - level gauge

a)
b)


Figure 2. General view of the experimental setup: a) from the side of the measuring unit; b) from the side of the measuring area

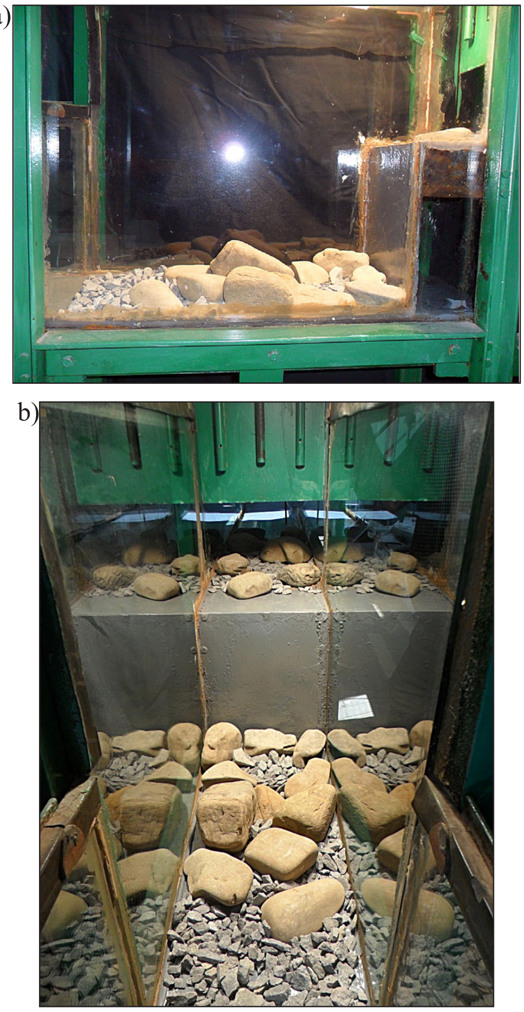
a)
b)


Figure 3. Area for modeling the flow of water through waterfalls and rapids: a) side view; b) view from the measuring area

RESULTS AND DISCUSSION

By changing the length of the tray section, the gullies and the waterfall niche of the real hydrodynamically active section were simulated, on which the field experiments on the Tyshivnytsia River were conducted. In the studies, measurements were performed at different flow regimes, which simulated different hydrological parameters. The influence of flow velocity, its depth and HAA structure on oxygen saturation parameters was determined. In order to analyze the impact of

Figure 4. Hydrodynamically active area on the Tyshivnytsia River, which is used for field research

HAA on the processes of self-cleaning, the flow was visualized using photography. The results of the research are shown in Figures 5, 6.

Figures 5-6 show the structure of the flow in hydrodynamically active areas, namely waterfalls, rapids and gullies. The figures shown above presented the formation of a waterfall niche in the case of flow through a waterfall and different types and magnitudes of the wave when the flow passes through rapids and gullies.

The presence of HAA in the mountainous and foothills of the rivers of the Carpathian region contributes to the processes of natural self-purification of natural waters. On the basis of the laboratory of wastewater treatment plants, the studies of factors and conditions of formation of chemical composition of natural waters of the basin of the river Stryi, and also sites of considerable anthropogenic influence were carried out. This allowed for more detailed monitoring of the

Figure 5. Visualization of water flow in experimental modeling of the flow through the waterfall: a) Q_3 = 0,0012 m^3/s; b) Q_4 = 0.0018 m^3/s

Figure 6. Visualization of water flow by modeling the flow through rapids and gullies: a) Q_3 = 0.0012 m^3/s; b) Q_4 = 0.0018 m^3/s

quality of natural waters of the basin, focusing more attention on the identified problem areas of negative impact.

It was found that in the river Stryi, there are quite active processes of self-cleaning, which are caused by the hydrological characteristics of the river and the presence of hydrodynamically active areas in the foothills of the basin. Therefore, at present there is no stable excess of pollutants relative to the MPC.

Further studies of the flow structure will allow offering refined calculation dependences and modern scientific methods for estimating the processes of self-treatment of surface waters and anthropogenic load in mountain river basins to calculate the optimal volumes of wastewater discharges from Treatment Facilities "Stryivodokanal".

CONCLUSIONS

The change of structure of a stream of natural waters at passage of HAA is established. The high oxygen saturation of the river waters of the Stryi river basin is caused by the influence of HAA, which contribute to the purification of polluted waters from biological and other man-made pollutants as well as contribute to the high quality of water resources in the region.

A method of modeling and visualization of mountain rivers in the laboratory was developed. By the method of experimental modeling it was proved that passing through hydrodynamically active sections of channels, mountain rivers of the Stryi river basin at different temperatures and flow velocities are maximally saturated with dissolved oxygen.

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