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Original Article

The parameters of flow-forming elements for controlling the behavior of fish in artificial channels

Os parâmetros de elementos formadores de fluxo para controlar o comportamento de peixes em canais artificiais

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Abstract

The current level of anthropogenic impact on open water sources shows a decrease in the quality of surface runoff, a constantly growing volume of water withdrawal for economic purposes, exerting the greatest significant impact and damage on the hydrobiological resources of water sources. The processes of interaction between subjects of hydro-biocenosis force us to study the mechanisms of interaction between fish, water flow, and hydraulic structure (channel), including the optimization of elements of hydraulic structures that affect the environmental safety of a water source as a whole. We noted the main formation patterns of the structure of a turbulent flow and its interaction with a hydraulic structure (channel), such as the pulsating nature of the aquatic environment, heterogeneous structure, gradient nature, and vortex structure. We analyzed the advantages and features of the effect of three-dimensional flow-forming elements on the behavior of fish. We developed the design and method of designing a bottom flow-forming element for controlling the behavior of fish in a river flow, substantiated geometrical parameters, created an optimal layout of bottom flow-forming elements in artificial channels. We provided an assessment of the use of technical solutions for flow-forming elements of existing and reconstructed fish protection facilities.

Keywords: channel bed, stream structure, fish behavior, fish-guiding device, stream-forming element.

Resumo

O nível atual de impacto antropogênico em mananciais abertos indica uma diminuição na qualidade do escoamento superficial, um volume cada vez maior de captação de água para fins econômicos, exercendo o maior impacto e danos significativos sobre os recursos hidrobiológicos dos mananciais. Os processos de interação entre sujeitos da biocenose aquática nos obrigam a estudar os mecanismos de interação entre peixes, fluxo de água e estrutura hidráulica (canal), incluindo a otimização de elementos de estruturas hidráulicas que afetam a segurança ambiental de fontes de água como todo. Observamos os principais padrões de formação da estrutura de um escoamento turbulento e sua interação com uma estrutura hidráulica (canal), como a natureza pulsante do ambiente aquático, sua estrutura heterogênea, natureza gradiente e formação de vórtices. Analisamos as vantagens e características do efeito de elementos tridimensionais formadores de fluxo no comportamento dos peixes. Desenvolvemos o projeto e o método de projeto para um elemento formador de fluxo de fundo visando controlar o comportamento de peixes em um fluxo de rio, substanciamos parâmetros geométricos, criamos um layout otimizado para elementos formadores de fluxo de fundo em canais artificiais. Fornecemos uma avaliação do uso de soluções técnicas para elementos formadores de fluxo em instalações existentes e reconstruídas para a proteção de peixes.

Palavras-chave: leito do canal, estrutura do córrego, comportamento dos peixes, dispositivo guia do peixe, elemento formador do córrego.

1. Introduction

The anthropogenic load on open water sources is manifested not only by a decrease in the quality of surface runoff (Snezhko et al., 2020) but also by a constantly growing volume of water withdrawal, primarily for economic purposes. At the same time, the greatest impact and damage is caused to the hydrobiological resources of water sources (Fish Protection Technologies and Downstream Fishways, 2005; Mikheev & Perelygin, 2007; Pavlov and Skorobogatov, 2014; Mikheev and Perelygin, 2014), the current situation is a necessary requirement

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and a convincing basis for carrying out comprehensive hydraulic and biological studies of existing problems in this direction. The complex processes of interaction between subjects of hydro-biocenosis force us to study the mechanisms of interaction between fish, water flow, and hydraulic structure (channel), including the optimization of elements of hydraulic structures that affect the environmental safety of a water source as a whole. For example, a stream (plume) forms at the tail of a fish, which is a kind of ordered coherent system of vortex formations. Obviously, the kinematics of such a flow is favorable for the advancement of the fish that follow it in the school, and, therefore, it can be used in the design of hydraulic engineering fish protection complexes and structures.

A review where the main studies on the problems and results of the analysis of the hydraulic structure of a turbulent flow in interaction with the body of various fish species and the characteristics of the behavior of fish in a water flow are considered is given in works (Pavlov and Pakhorukov, 1983; Fish Protection at Water Diversions, 2006; Borovskoy and Mikheev, 2011; Mikheev et al., 2019, 2020).

In this study, the benefits and characteristics of three-dimensional flow-forming elements' influence on fish behavior were examined. We developed the design and procedure for designing a bottom flow-forming element for regulating fish behavior in a river flow, validated geometrical parameters, and designed the best arrangement for bottom flow-forming elements in artificial channels. We evaluated the use of technical solutions for the flow-forming components of both the original and rebuilt fish protection facilities.

2. Material and Methods

The scientific approach to ensuring the control of fish behavior and the protection of ichthyofauna in water bodies is based on the patterns of formation of the structure of a turbulent flow and its interaction with a hydraulic structure (channel) (Karaushev, 1960; Schlichting, 1969; Idelchik, 1975; Abramovich et al., 1984; Samoilovich, 1990; Larinier & Travade, 1999):

- The pulsating nature of the aqueous medium [the pulsations of the instantaneous values of the kinematic and dynamic parameters determine the fact that, in the strict sense, the turbulent motion of a fluid is unsteady (even if its averaged characteristics do not change over time)];
- Heterogeneous flow structure (affects the distribution of fish in the living section of the river, this is especially noticeable in the downstream of the hydro-units during spawning migrations with uneven discharge of water from the reservoir through the spillway dam spans);
- The gradient distribution of velocities (gradient areas in the river are created naturally by the entire surface of the river bed, streamlined solid objects (stones, trees, ledges, etc.), channel vertical - ridges, and planned - meanders);
- Vortex structure (vortices of natural river turbulence allow fish to use their energy to accelerate their movement upstream to the spawning site).

Hydro-biological features of the orientation of fish in the water flow are characterized in works (Lighthill, 1969; Pavlov and Pakhorukov, 1983; Pavlov and Skorobogatov, 2014):

- A kinematic-morphological model of the types of drivers of biological objects in the aquatic environment (the analysis of vortices generated by biological objects in their motion made it possible to identify only a few characteristic forms of structural vortex objects in the aquatic environment, known as classical in the theory of flows liquids and gases);
- A variety of types of movement, physiological characteristics and behavior of aquatic animals (the composition of the geometric model is limited to several basic types of biological propulsion in the aquatic environment: locomotor wave; oscillation (method of creating a jet stream by oscillation of the tail fin); rowing; jet stream);
- The relationship with the hydrological and hydrodynamic parameters of the flow and channel (during the period of spawning migration, fish moves at the lowest speeds and areas with high turbulence, due to the need to save their energy);
- The use of the wave energy of a turbulent flow near the wave surface of the mixing layer, the jet (studies show that fish (as well as birds) can use the wave energy of the flow);
- Rheoreaction as the main receptor in determining the direction of movement (the direction of flow for fish is a kind of navigator).

Under the regulated flow, when the hydrological conditions of natural watercourses of fishery importance change significantly, the conditions and behavior of fish change.

3. Result and Discussion

We optimized hydraulic conditions to substantiate the geometric parameters of the structures of fish protection structures and devices as a tool for controlling the behavior of fish in a stream near water intakes and fish-passing structures.

- Optimal hydraulic conditions for the movement of fish during spawning migrations are those formed with a variety of forms of natural watercourses, complex relief, providing a wide range of velocities and forms of currents for a rational combination of functions of orientation, movement, rest, spawning, etc;
- In the downstream of waterworks, when a large number of fish accumulate during spawning migrations, fish navigates with the help of flow-forming elements that create a favorable kinematic structure of the flow for moving fish to the entrance to the fish-passing structure;
- The shape and dimensions of the flow-forming element in the channel depend on the hydraulic characteristics of the flow, the size of the channel-forming sediments;

- The optimal shape of the flow-forming surface, which corresponds to a rational combination of hydraulic factors in the river channel, is a hierarchical relief structure close to fractal;
- The optimal shape of the flow-forming element to create conditions for the passage of fish along the river bed is a dune - an element of a small ridge, modeled by riffles;

Biologically, the “dune” as a flow-forming element, in comparison with a two-dimensional element, has the following advantages and features:

- a three-dimensional nature contributes to the formation of a stagnant zone, a recreation area in the aft part (in the basement);
- the attached “dune” vortices form an ascending structure of currents, providing favorable conditions for water exchange for the passage and rest of benthic fish species;
- during their formation, the “dunes” are practically isometric in plan, with the length-to-width ratio $L / b_{\partial} \approx 1$, and the number of types of channel forms, which is due to the hydraulic characteristics of the flow and is N_{cf}=5 – 9 (Borovskoy and Mikheev, 2011);
- the optimal angle of navigation in terms of the downstream slope is the angle coinciding with the angle of wave propagation $\alpha_{б} = 36^{\circ} - 40^{\circ}$;
- the downstream slope of the dune is taken to be close to the value of the repose slope of sand in the water within $\alpha_H = 30^{\circ} - 35^{\circ}$;
- the height of the ridge $h_г$ is determined by the height of the active ridge-forming bottom roller and depends on the value of the form parameter n included in the formula for the wave profile of the boundary layer velocity;
- the staggered “dunes” at the bottom of the river manifest itself as the duration of the steady motion of the liquid in the moving channel increases.

To determine the geometrical parameters of the “dune” element and design of the optimal layout and structural scheme for the placement of flow-forming elements in the river bed, the design scheme shown in Figure 1 is used.

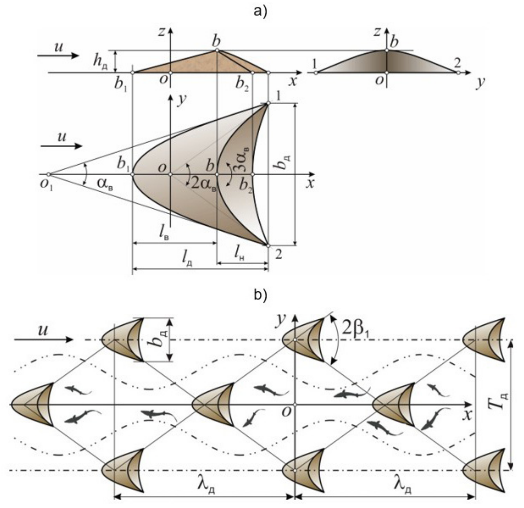

Figure 1. The dune-type flow-forming element design scheme.

3.1. The dune-type flow-forming element geometric parameter design procedure

Given the above, the geometric parameters of the elements of the dune-type flow-forming system are calculated in the following logical sequence (Figure 1).

The hydrological and hydraulic characteristics of the considered open flow serve as the initial data. The main hydrological characteristic is the channel-forming flow rate and the following hydraulic parameters indirectly related to it in its determination: channel-forming profile of averaged velocities; average velocity in the free flow section V; depth H; wetted perimeter χ; hydraulic radius R; channel bottom roughness factor Δ_e. The characteristic profile is used to determine the value of the maximum vertical velocity u_m.

The calculation constants are kinematic viscosity ν; angular parameter (wave parameter) $\phi_{t_H} = 30^{\circ}$; the characteristic angle of the diagonal arrangement of the flow-forming elements with the rhombic arrangement in the channel bed $\beta_1 \approx 36$; the downstream slope, which is taken to be equal to the repose slope for sand in water, is $\alpha_Н = 30^{\circ} - 35^{\circ}$; the ship wave propagation angle is $\alpha_B = 36^{\circ}$.

The shape of the given channel-forming profile of the averaged velocities of the considered flow is compared with the shape of the wave profile of the boundary layer velocity, built for different values of the shape parameter n according to the following parametric Formula 1

$$\frac{u}{u_m} = \left(\frac{1+\cos\theta}{2}\right)^{1/2n} ; \quad \frac{y}{y_m} = \frac{\theta - \tan^2 \varphi_{t_H} \cdot \sin\theta}{\pi} \tag{1}$$

The taken calculated value n is one at which the dimensionless profiles are aligned and become affine. Shape parameter n (as well as the Darcy coefficient of hydraulic friction λ) depends on the Reynolds number $\mathrm{Re} = \frac{VR}{\nu}$, i.e., $n = f(Re)$ and is an alternative to the Reynolds number, succinctly and comprehensively characterizing the degree of flow vortex formation by the profile shape (Loytsyansky, 1987; Prandtl, 2000; Borovskoy, 2009).

The dune geometry is determined by four linear ($h_д$, $l_д$, $b_д$ $l_Н$) and two angular ($\alpha_в$, $\alpha_Н$) parameters. The height of the flow-forming element of the “dune” type coincides with the vertical size of the characteristic channel form of the river flow $h_д = h_{гmax}$, calculated by the following Formula 2:

$$\frac{H}{h_{Гmax}} = \sum_{i=1}^{n} 3^{i-1} \quad \text{or} \quad h_{Гmax} = \frac{H}{\sum_{i=1}^{n} 3^{i-1}} \tag{2}$$

The dimensions of the dune length $l_д$, width $b_д$ and depth of the downstream slope $l_Н$ are found from the conditions of the rational outline of the element shape according to the following relationships Formulas 3, 4, 5:

– width $\dfrac{b_\partial}{T_\partial} = \dfrac{1}{1+\Phi}$ (3)

– length $\dfrac{l_Д}{b_Д} = \dfrac{1}{2}\cos\left(\dfrac{\alpha_в}{2}\right)\left[\dfrac{1}{\sin\left(\dfrac{\alpha_в}{2}\right)} - \dfrac{1}{\sin\left(3\dfrac{\alpha_в}{2}\right)}\right]$ (4)

– depth of the downstream slope $\dfrac{l_н}{b_Д} = \dfrac{1}{2\mathrm{tg}\left(3\dfrac{\alpha_в}{2}\right)}$ (5)

The shape of the arcs of the flow-forming element is taken to be parabolic according to the condition that the functions pass through three points (in the plan), and the tangents at points 1 and 2 coincide with the angles due to the geometric structure of the five-pointed star $\alpha_в = 36^o$, $2\alpha_в$ and $3\alpha_в$.

To arrange the flow-forming elements at the bottom of the channel checker wise, the pitches for the transverse and longitudinal arrangement of the elements should be determined in the corners of the rhombuses. The distance between two dune tops in the cross-section of the channel $T_д$ is calculated by the Formula 6

$$\frac{T_Д}{H} = \frac{4b_{яц}}{H} = \frac{4}{\cos(\pi/6)} \approx 4,62 \quad (6)$$

Where $b_{яц}$ is the width of the transverse circulation cell, determined by the Formula 7

$$\frac{b_{яц}}{H} = \frac{1}{\cos\varphi_{tн}} \quad (7)$$

The longitudinal arrangement pitch of the flow-forming elements is determined by the Formula 8

$$\lambda_Д = T_Д / \mathrm{tg}\beta_1 \quad (8)$$

The resulting procedure allows moving on to the gradual implementation of practical tasks:

- firstly, form the optimal structure of tactile and hydraulic reference points in the channels of canals and rivers to ensure the directional movement of fish (fish-passage and fish-passage-spawning channels);
- secondly, ensure the safe transfer of fish fry from the fish protection structure to the fish receiver in the sections of the fish-diverting tract with bottom slopes more than critical by means of fast-flow chutes with flow-forming elements.

An assessment of the use of flow-forming elements of the chutes of the connecting structures of the fish-diverting tracts of the fish protection structures is given below.

3.2. Fish protection structure of the water intake of the Azov irrigation system

The fish diversion tract in a section with a sharply broken terrain relief is equipped with a mating structure in the form of a fast-flow chute with a calculated slope $i = 0.165$ and artificial roughness in the form of steps with a horizontal section 0.75 m long and a slope element 0.25 m long with a setting equal to one. However, in the process of construction, the flume chute was made with a slope $i = 0.129$, and the flow-forming part was in the form of horizontal steps depressed at the beginning (Figure 2).

The changes made it possible to increase the effect of damping the kinetic energy of the flow and to provide the necessary velocities for the safe movement of fish.

3.3. Fish protection structure of the water intake of the Donskoy Main Canal (DMC)

If there are command levels of water in the fish diversion chamber, the diversion of fish fry can proceed by gravity using a mating chute. The project for the reconstruction of the fish protection structure of the DMC provides for a monolithic reinforced concrete chute of rectangular cross section, constant width with a cantilever end section.

The basic geometric and kinematic characteristics of the flow along the length of the chute were obtained by hydraulic calculation of the connecting chute of the fish diverter for the minimum and maximum flow rates.

With a smooth surface, the calculated flow rates at the end of the chute have a significant value that is dangerous for fish fry (> 7.0 m/s). To reduce the speeds in the connecting chute, a variant of the arrangement of bottom flow-forming elements was considered.

A stepped chute was considered as a possible option for the use of bottom flow-forming elements in the chute, with

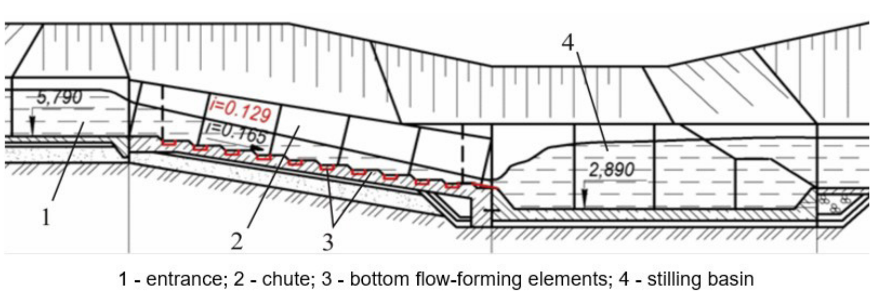

Figure 2. A coupling structure in the form of a rapid flow in the fish diversion channel.

the step parameters: length along the stream 800 mm and height 100 mm. The hydraulic calculation made it possible to establish the main parameters of the flow; with a water depth 0.5 m at the end of the chute, the adopted design makes it possible to reduce the maximum flow rates to the required ones - 5.0 m/s.

When the flow of the fast-flow chute is coupled “level to level” with the flow of the fish diversion tract and with the minimum depth in the channel 1.7 m, the safety conditions for fish fry correspond to the required ones.

4. Conclusion

Based on the analysis of the hydraulic structure of the turbulent flow in interaction with the body of various fish species, the conditions for the formation of channel bottom topography, a method for calculating the parameters and a layout diagram of the placement of a bottom dune-type flow-forming element for controlling the behavior of fish in the channels of canals and rivers has been developed. An assessment of the use of technical solutions for flow-forming elements of existing and reconstructed fish protection structures is provided.

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