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INNOVATIVE DESIGNS FOR FISH-PASSING FACILITIES: A PATHWAY TO SUSTAINABLE AQUATIC ECOSYSTEMS

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ABSTRACT: Fisheries are an important economic component of the Republic of Kazakhstan, covering an area of 25.475 hectares throughout the country. However, fish are threatened by natural and artificial obstacles such as heavy rains, droughts, floods, and electricity consumption. Although fish enclosure structures can offer protection, designing new, more efficient fish-passing facilities is crucial. This study aimed to develop a model for a fish-passing facility, with experiments conducted at the Dulati Taraz Regional University in the laboratory of hydraulic structures and land reclamation. Researchers built a laboratory model of the facility and compiled an analytical model of the proposed technical solution. The study calculated the optimal values of the additional pressure and axial velocity of the total flow based on the required attracting flow. The practical significance of this research is in the ability to create a controlled high-speed flow regime in the fish-passing tract, which would provide favourable conditions for the passage of different types of passing and semi-passing fish through the hydroelectric facility dam, despite significant fluctuations in the headwater levels. The scientific nature of this research is evident in its contribution to the broader knowledge base in the field of fisheries and ecological engineering. The study expands our understanding of fish behaviour and provides new insights into the design of fish-passing facilities.

Keywords: Modelling, The problem of fish protection, Hydraulic jets, Land reclamation, Hydroelectric complex

1. INTRODUCTION

Kazakhstan is rich in fish resources. It is the fishing industry that can play a special role in the economic development of the country. A lot of work has been done in this industry recently. And today, due to the initiatives taken by the government, the fishing industry is developing quite successfully. In August of 2021, the Head of State pointed out the need to develop existing opportunities and instructed to develop and approve regional programmes for the development of the fishing industry by November. East Kazakhstan is the region with the most developed fishing industry in the country. In the region, there are 59 commercial and 97 small fishing areas on bodies of water. The annual production is about 10 thousand tonnes of fish from 12 main commercial fish species. In 2021, the catch limit has been brought to the amount of 10.2 thousand tonnes. The largest volume of catch, up to 93%, falls on Lake Zaysan and the Bukhtarma reservoir.

Almost half of the country's lakes are located in the North Kazakhstan region. There are 26 fish farms operating on the territory of the region, located on 52 reservoirs, in the form of a lake-commodity fish farm. Sixty-nine people are employed [1]. Due to the decision of the First President – Elbasy N. Nazarbayev, the northern part of the Aral Sea was restored, and thousands of fishermen returned to the trade of their grandfathers. The founder of TOO "SPK Kyzylordabalyk" Amanbay Yerkhatov described how the fishing industry in the region is developing today [1]. Another area rich in fish is Turkestan. Commercial fish farming (aquaculture) is especially developed there. The region is in first place in terms of the volume of fish grown. In the region, the number of lakes suitable for growing commercial fish is 134 units, and the total area is 25.475 hectares (Figure 1). Of these, 23 reservoirs of local significance were transferred to users of natural resources for fishery purposes, and 21 reservoirs of local significance were additionally issued for competition [1]. Admittedly, seasonal, weekly, and daily fluctuations of the water pools are characteristic of river hydroelectric complexes. This is primarily conditioned upon changes in the hydrological situation on rivers (flood, shallowing during drought, increase in water level during heavy rains, etc.), and weekly and daily generation (consumption) of electricity [2-4].

Fig. 1. Water resources map of Republic of Kazakhstan

Fig. 2. Improvised fish passing structure

As evidenced in the studies by Western European specialists, the most rational fish protection devices are fish enclosures using the hydraulic method in the form of bottom sills obliquely directed to the dynamic axis of the flow [5-8]. In contrast to the mechanical method of fish protection in the form of protective nets and gratings, this hydraulic method appears to be more effective and safer on the channel heads. In comparison with acoustic, electrical, optical methods, the proposed method is cheaper and more reliable for mountain rivers [9].

There are known fish passing locks [10] containing a section of the river turned into a lock chamber, an upper head, a lower head and a bypass channel with gates. These structures are not compulsory, but their work is cyclical. In conditions of small rivers, the lock chamber can be a section of the river along the entire width (Figure 2).

As part of large waterworks, a gateway can be built on a bypass channel (breeding and passage waterways). The common disadvantages of the above-mentioned fish-passing facilities are: their considerable length and unsatisfactory economic indicators and the difficulty of placing the entrance part near the migration route, which reduces the efficiency of their operation. A fish-passing facility is also known [11], which includes a working chamber with gates, an outlet chamber, a fish accumulator and a fish-guiding device in the form of a tray made in the bottom of the lower stream at an acute angle placed between the upper lower reaches of the hydroelectric complex. In the expanses of the post-Soviet space, the main activity in this area was to increase the efficiency of passing fish through hydroelectric complexes with cyclical fluctuations in headwater levels by making changes in the design of fishing facilities using hydraulic jets [12-15]. But it is necessary to consider the flow rate of the flowing liquid using an automatic water level sensor in open reclamation canals [16; 17].

This article will help design new, as well as upgrade existing fish-passing facilities. Modernization of fish passages can positively affect the ichthyofauna both in Kazakhstan and all water bodies of Central Asia.

2. RESEARCH SIGNIFICANCE

The research on designing new fish-passing facilities is of significant importance due to the increasing threats posed to fish habitats in Kazakhstan. The construction of hydroelectric facilities and natural disasters such as floods and droughts create barriers for fish passage, which negatively impact their populations. The study of fish-passing facilities provides a way to mitigate these negative impacts and ensure the preservation of fish habitats.

This research can also have implications for the construction of fish-passing facilities in other regions facing similar challenges, thus contributing to the sustainable management of fisheries and aquatic ecosystems.

3. MATERIALS AND METHODS

During the experiments at the Dulati Taraz Regional University, in the laboratory of hydraulic structures and land reclamation, a study on the doctoral topic was conducted. Taking the above material and the technical theoretical materials of researchers from other countries, experimental work was carried out. The design of hydraulic structures (HS) is carried out using CAD (computer-aided design system) and with the involvement of various computing systems for modelling flows in HS facilities and equipment. The FishSim computer-aided engineering system (CAE) is being developed for the design of fish-passing facilities. It includes a set of programmes for modelling unsteady turbulent water flows in open-surface fish-passing chambers and calculating the dynamics of fish movement in these facilities. A configurable behavioural model of their movement as separate agents of independent or interconnected fish individuals were introduced into the system [18-21]. The computing system is designed to carry out optimisation calculations when choosing the designs of fish passages, lifts, and other devices that ensure the passage of valuable fish species through the hydraulic structures [22].

The system contains blocks for calculating the hydrodynamics of currents in fish-passing facilities and modelling the movement of fish in them. To calculate stationary and non-stationary turbulent flows, it is possible to use the SINF programme used as part of the SELIGER system [18] and the FLOW-3D programme [19]. To simulate flows with a free interface between water and air, the VOF method is used with the introduction of the transfer equation of the porosity function of a two-phase medium [19]. The simulation of fish movement is carried out on a pre-calculated field of water flow velocities in the facility. The calculation is carried out with the involvement of the behavioural model of the fish. During its generation, the experience of substantiating two-dimensional models of the movement of a school of fish in traps when they bypass obstacles are considered [20; 21]. The behaviour of fish is motivated by the purpose of their combined movement aimed at exiting the fish hatchery upstream, considering the flow modes in the labyrinths of flow chambers and the local structure of water jets in the areas of inlet openings and drops.

The illustration below (Figure 3) depicts a sample ladder-type fish-passing facility.

Fig. 3. Ladder-type fish-passing facility

4. RESULTS AND DISCUSSION

In the process of work, the obtained useful models of the fish-passing facility were taken as a basis [23]. They consist of separate pools of the following sizes: width – 1.2 ...13.5, length – 2...2.5 m, water depth – 1.2... 1.75 m, drop – 0.3-0.5 m for sturgeon and carp, and 0.15 ...0.25 m for pikeperch, marinka, crucian carp, etc. In the transverse walls separating the pools, the inlet holes are arranged, which are located alternately at the right, then at the left walls (for sturgeon – at the bottom, for carp – at the surface). Hole sizes – from 0.2x0.3 to 1x1.5 m. And also, to increase the efficiency of attracting fish, in addition, a transit part is made in the form of a rapid flow on both sides of the stepped trays. The calculation of turbulent flows is based on the RANS equations (Reynolds averaged Navier-Stokes equations) using the k-turbulence model (Figure 4).

This is done for large fish that are used to climbing up on a smooth surface on their own. The desired result is achieved by installing a fish-passing facility with stairs in the form of stepped trays, consisting of separate pools of the following sizes: width – 1.2 ... 13.5, length – 2 ... 2.5 m, water depth – 1.2 ... 1.75 m, drop – 0.3 ... 0.5 m for sturgeon and carp, and 0.15... 0.25 m for pike perch, herring, etc. Venting holes are arranged in the transverse walls separating the pools, which are located alternately at the right, then at the left walls (for sturgeon – at the bottom; for carp – near the surface). And also, to increase the efficiency of attracting fish, additionally, on both sides of the stepped trays, a transit part is made in the form of a rapid flow for large fish that are accustomed to independently climbing up on a smooth surface [24-26]. Figure 5 shows the diagram of the fish-passing facility in the form of stepped trays and the 2-2 transverse section of the stepped tray.

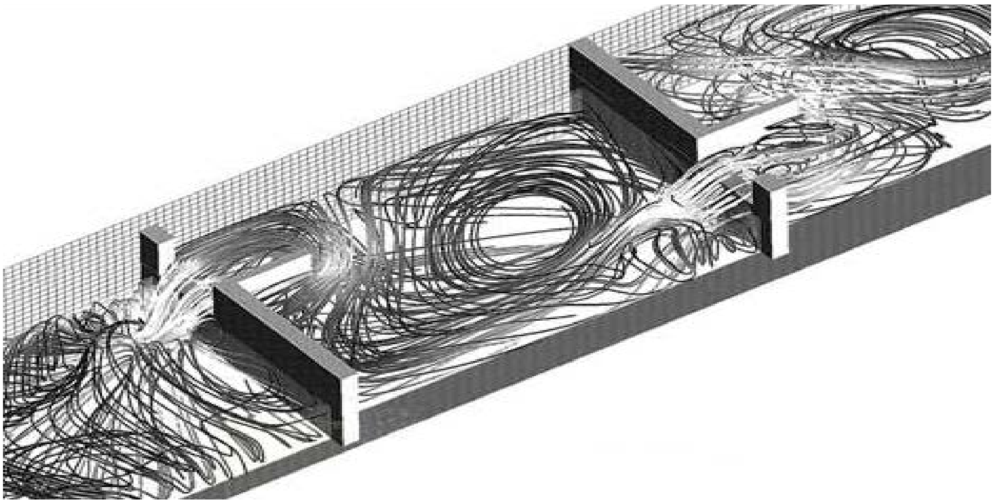

Fig. 4. Vortex generation in the chambers of a ladder-type fish-passing facility with an upper spillway

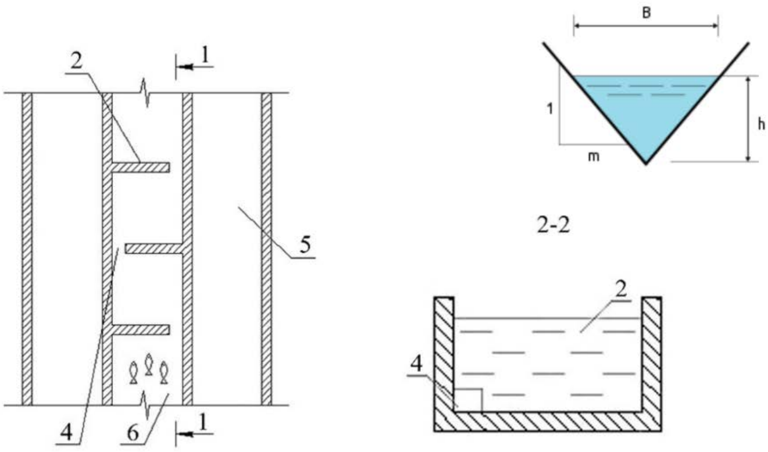

Fig. 5. The diagram of the fish-passing facility and its cross-section

The fish-passing facility consists of a longitudinal wall 1, a transverse wall 2, stepped trays 3, inlet openings 4, and a transit part on both sides of stepped trays in the form of a rapid flow 5. The device works as follows. The arrangement of a fish-passing facility made of stairs in the form of stepped trays 3, consisting of longitudinal 1 and transverse 2 walls, is made for the successful passage of fish from one wall to another. The inlet openings 4 arranged in the transverse walls 2, located alternately at the right, then at the left walls – are favourable for the fish migration upstream. The transit part in the form of a rapid flow 5 on both sides of the stepped trays is arranged for large fish that are accustomed to independently climbing up on a smooth surface without getting into the stepped trays.

During the laboratory study, there was a scaling of 1:100, which is shown in Figure 6, and laboratory results were taken.

Analytical model of the proposed technical solution. Hydraulic jets, flowing out of the jet-forming nozzles and interacting with each other, form a total flow. The total flow creates a zone of partially equal pressures in front of the inlet of the fish passage, which makes the passage of fish and other aquatic inhabitants into the upper stream unobstructed. The mathematical condition for the generation of a zone of partially equal pressures has the following form [12; 15; 24]:

$$V_{UO} = \sqrt{gH}, \quad (1)$$

Where: V_{UO} – initial axial velocity of the total flow; g – acceleration of gravity (m/s^2); H – the amount of pressure falling on the transverse dividing wall (m). The initial axial velocity of the total flow is V_{UO} found using the equation:

$$V_{Uo} = \varphi \frac{V_0 \, d_{o_n}^{\frac{2}{3}} b_э^{\frac{1}{3}} n}{9.514\,(h_e - b_э)}, \quad (2)$$

Where: V_{Uo} – initial axial velocity of the total flow; φ – dimensionless coefficient, experimentally determined; V_0 – initial velocity of the hydraulic jets from jet-forming nozzles (m/s); d_{o_n} – diameter of jet-forming nozzles (m); $b_э$ – distance between the axes of hydraulic jets (m); n – number of hydraulic jets in a row; h_e – distance between the plates of the distribution of hydraulic jets (m). Figure 7 shows the 1-1 longitudinal section.

The magnitude of the dimensionless coefficient depends on many factors, the main of which is the size of the inlet opening and the configuration of the location of the jet-forming nozzles [27]. Experimental studies show that the values of the dimensionless coefficient are sufficiently accurate to solve most practical problems in the range of 0.001 to 4.00. It is necessary to have a stable attracting flow coming through the fish-passing facility [28]. For its generation, an additional pressure H is created, the value of which is determined from the following equation:

$$\Delta H = H - \frac{V_{Uo}^2}{g}, \quad (3)$$

Where: ΔH – the magnitude of the additional pressure.

Thus, the additional pressure ΔH is the difference between the actual value of the pressure H, which falls on the transverse dividing wall, and the pressure created by the total flow [29-30]. The value ΔH (Table 1) must be set depending on the type of fish moving along the passage. Table 1 shows the optimal values of ΔH depending on the required attracting flow, calculated by known methods.

Fig. 6. Laboratory layout of a fish-passing facility 1:100

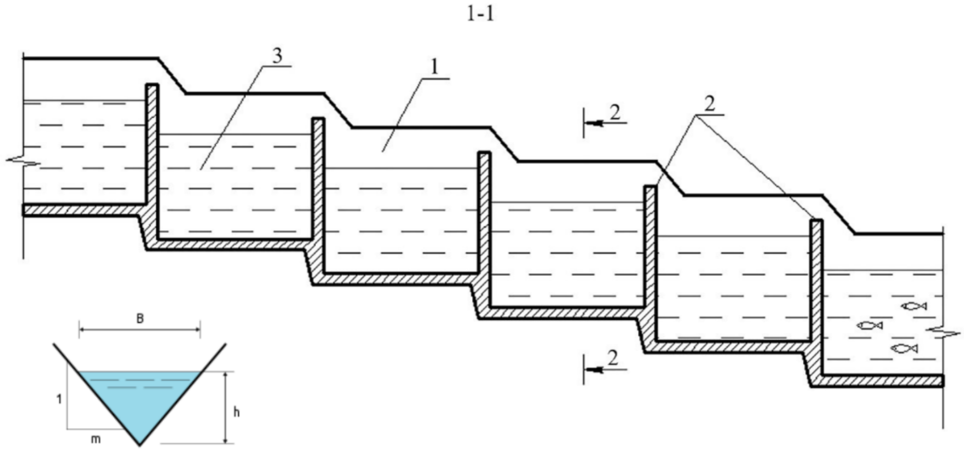

Fig. 7. Longitudinal section of the fish-passing facility

Table 1. Optimal values of ΔH depending on the type of moving fish

Type of fish	Optimal values				Maximum values			
	attracting speed, m/s		additional pressure ΔH, m		carrying speed, m/s		additional pressure ΔH, m	
	min	max	min	max	min	max	min	max
salmon	0.90	1.40	0.26	0.63	1.10	1.60	0.39	0.82
sturgeon	0.70	1.20	0.16	0.46	0.90	1.40	0.26	0.63
small fish	0.50	0.80	0.08	0.20	0.90	1.20	0.26	0.46

5. CONCLUSIONS

The research provides critical findings in response to the specific research question of how to develop efficient fish-passing facilities to ensure the sustainable management of aquatic ecosystems in the Republic of Kazakhstan. The study demonstrates the potential benefits of utilizing hydraulic jets in fish-passing facility designs. The uniqueness of the study lies in the study of the integration of hydrojet technology in the design of fish hatches and the study of its potential in solving the problems associated with fluctuations in the upper water levels and various fish species.

Thus, the ability to compensate for significant pressure fluctuations at the hydraulic unit with the help of hydraulic jets in one inlet opening alone would allow the following:

– to significantly reduce the length and material consumption of the fish passage;

– to ensure the possibility of a passage for new fish through the facility – passage not only for salmon but also for other passing and semi-passing fish species;

– to fully link the operation of the fish-passing facility to the features of the hydroelectric complex with the cyclic operation;

– to preserve the naturalness of conditions for the passage of migrants and fulfil environmental requirements.

The proposed changes in the designs of fish passages based on the technology of hydraulic jets and their modes of operation for passing fish through hydraulic complexes allow creating of a controlled high-speed flow regime in the fish-passing tract, which would provide favourable conditions for the passage of various types of passing and semi-passing fish through the dam of the hydroelectric facility with significant fluctuations in the headwater levels.

While these findings contribute to the advancement of fish-passing facility designs, they also highlight potential areas for future research. Further investigation could explore:

– The application of the proposed hydraulic jet technology in different environmental conditions and geographical settings, ensuring its adaptability and effectiveness across various scenarios.

– The long-term effects of these innovative designs on aquatic ecosystems and fish populations, confirming their sustainability and ecological benefits.

– The development of monitoring and evaluation systems to assess the performance of fish-passing facilities and inform ongoing improvements in their design and operation.

In summary, the research presents valuable findings regarding the development of efficient fish-passing facility designs using hydraulic jets. This study differs from existing literature by focusing on the integration of hydraulic jet technology in fish-passing facility designs and exploring its potential in addressing challenges related to fluctuating headwater levels and diverse fish species. These findings not only offer practical solutions for current challenges but also lay the groundwork for future research, aimed at ensuring the long-term sustainability of aquatic ecosystems and the effective management of fisheries resources in the Republic of Kazakhstan and beyond.

6. ETHICAL STATEMENT

Informed consent was obtained from all individuals included in this study.

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