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HYDRAULIC RESEARCH FOR SUCCESSFUL FISH MIGRATION IMPROVEMENT – ”NATURE-LIKE” FISHWAYS

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This article presents an overview of the design solutions for fishways which are locates nearby hydrotechnical constructions. Currently fashionable and recommended hydraulic design of fishways are moving towards "close to nature" solutions. Their characteristic feature is applicable to the construction a natural building materials (tree trunks, stones, gravel, vegetation) in such a way that its appearance resembled a small natural water courses. Design of hydraulic fishways based solely on the criteria of maximum speed v_{max} and *parameter of unitary energy of water E*, it does not give complete information about the effectiveness of these devices. In order to produce the optimal flow conditions for ichthyofauna, very useful are spatial structure research of hydraulic parameters, such as disorders of velocity field or the degree distributions of turbulence *Tu*. The article presents an example of such a study, which the authors carried out on the model seminatural fishway in the water laboratory in Institute of Environmental Engineering in Wrocław. The results were used to assess the accuracy of the functioning of the fishway.

Keywords: fish ladders, hydraulic conditions of water flow, model test

1. INTRODUCTION

The loss of ecological permeability of the rivers, very often is associated with hydrotechnical constrictions of riverbeds. On the other hand, an artificial barriers like the dams, weirs, thresholds, etc. are in many cases necessary for the regulation of rivers, flood protection, retention, water balance and management in the catchment, agriculture and environmental needs in adjacent areas. Hydroelectric power plants also contribute in ecological production of electricity.

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Polish accession to the European Union, forced ecological operations in the widely understood water management. For instance, in order to allow the fish to overcome damming, free migration and reduce their mortality in hydroelectric turbines, the law requires a special structures in the vicinity of hydrotechnical obstacles, so-called fishways. Taking into account the structure, the type of materials which they are made and the hydraulic flow conditions prevailing inside the construction of fishpassages, they can be divided into: technical and "close to nature"/seminatural/ [3, 5, 12, 15, 18].

Fig. 1. Baffle fishway in Schleusingen/Gernany (photo Tymiński)

Fig. 2. Vertical slot fish pass by Villach/Austria [9]

Technical fishways are the oldest known structure to allow fish upstream migration. We can distinguish the following types of devices: baffle fishways (Fig. 1), fish ladder of the reverse current (Denil fishway), vertical slot fishways (Fig. 2), eel's gutters, locks and fish elevators. Technical ladders are well described in the professional literature [1-2, 5-7, 9-13, 15-16] and therefore will not be a theme of certain research. Most of them are not difficult to hydraulic dimensioned and until recently a designers willingly chose technical solutions of fishways. Technical ladders are built mostly of concrete. This fact makes that they are compared to nature and local foreign prosthesis. Currently fashionable and recommended hydraulic design of fishways are moving towards solutions "close to nature" - a fishways with biological build-up.

2. THE NATURE-LIKE FISHWAYS

Close to nature fishways are more modern than solutions of technical ladders type. Long research and analysis of hydraulic fishways design and better understanding of the environmental determinants of ecosystems, led to emergence of solutions that will enable aquatic organisms to overcoming obstacles in conditions similar to natural way. At the same time, these ladders should allow for the proper functioning of the hydrotechnical object and harmoniously interact with the surroundings. Hallmark of "close to nature" fishways is applied to their design natural materials such as wood, vegetation, stone, gravel and river bed load - molded in a specific way for each type of structure. To nature-like fishways we can include:

- rock-ramp fishways (rapids, ramps),
- chain of reservoirs,
- by-pass channels (seminatural bypass fishways).

2.1. Rock-ramp fishways

Rock-ramp fishways otherwise artificial rapids or ramps are the constructions, that reflect the steep drop in the river bottom slope equivalent 1: 20-1: 30. They are made of stones with a diameter from 30 to 80 cm. The size of the material should be precisely selected to ensure a suitable water velocity and the amount of flowing water. The material used for the construction of the ramp should be the stones from the nearby surroundings. There is a division of the ramp due to their location. We can distinguish:

- ramps arranged over the whole width of the riverbed,
- ramps arranged in part of the riverbed (built in additional narrow overflow hole of hydrotechnical object, separated by a partition structure from the rest),
- ramps such a stream, which revolve around a hydraulic obstacle (for instance: a weir).

Thesecond group of these fish-passes are:

- ramps pool,
- erratic-ramps – irregular heap up stones.

Cascades
The cascades are small collections of pools connected with each other with a little ramps angle or a number of steps with a low gradient (Fig. 3).

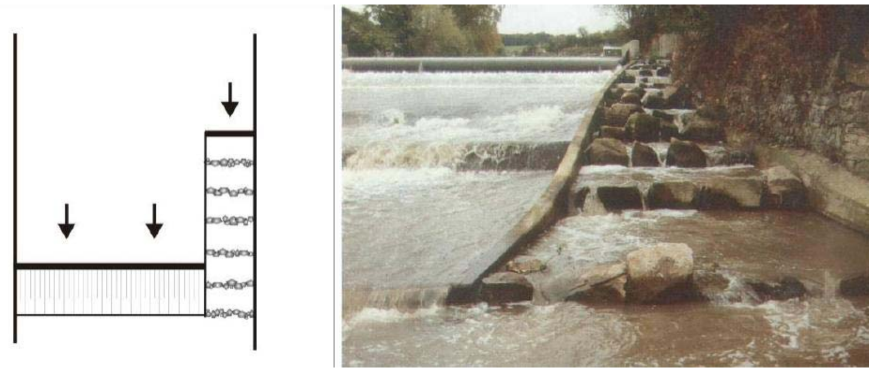

Fig. 3. Rock-ramp fishway [6]

Ramps
Resemble stone ramps, but their shape is more regular. They are built with stones and boulders reinforced by concrete. Here you can highlight the ramp boulders made of layers pour off rocks and boulders, also with deck-mounted ramps - edgewise embedded boulders. Sometimes the ramps can be spread across the entire width of the watercourse, however, are more likely to meet the ramp on one side of the shore.

2.2. Chains of basins

In this case, the crossing for fish are connected to each other with small basins, ponds, which are located on the ladders (Fig. 4). Following basins are connected by short overflows. Another variation of this type of ladder is step-pool fishway.

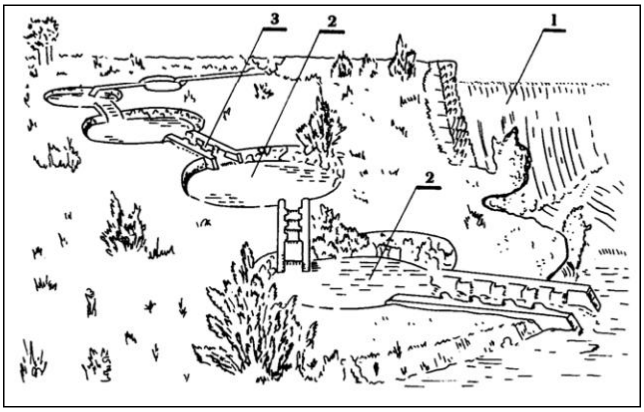

Fig. 4. Chains of basins: 1-artificial barrier , 2-basin, 3-ramp [20]

Ponds are places where fish can rest during the journey. They also have the role of speed reduction on the ladders. In this type of system, the arrangement of intermediate pools are usually irregular and varied, the main cause of this type of asymmetry are off-road conditions [15].

2.3. By-pass channels

By-pass channels (circulation channels) are constructions resemble a rivulet or mountain stream (Fig. 5). This type of ladder has a dual function - it is a temporary way to fish as well as a permanent habitat for other organisms. The first such ladders originated in countries highly urbanized, where as a result of the river adjustment many natural habitats were destroyed.

To build a popular by-pass channel we must use natural materials as stones, gravel, tree stumps, boulders, fascines, etc. The bottom of the ladder is also composed of similar elements. Its slope varies in the range of 1:75 to 1:20. It is formed by natural depressions and pools, which automatically reduces too high velocity of water. By-pass channel must be leaded a winding route, resulting in minimizing the velocity and to reduce the difference between the downstream and upstream level. If the designers have at their disposal a relatively much space to build, there is possible to reduce the impoundments even up to 10 m. Under these conditions, the circumvent is more diverse and has sections characterized by large and small declines [5, 8].

The disadvantage of this kind of transition is that to function properly there must be a large flow of water. Unfortunately, may occur such hydrological and hydraulic conditions, that this requirement will not be fulfilled.

Fig. 5. Semi-natural bypass fishway in the old river bed of the Rhone/France [10]

3. RECOMMENDATIONS FOR FISHWAY DESIGNERS

In Poland, the design guidelines for fishway drawn up by a German interdisciplinary expert team [2, 6, 7, 13, 14] are popular and commonly used. A summary of its key assumptions is given in the Table 1.

Table 1. Ichthyofauna Requirements and Guidelines for Fishway Design [2, 6, 7, 13]

Type of fish	*Permissible water flow velocities in fishways*
Small fishes and juveniles	$v < 1.0$ m/s
Medium-size fishes like cyprinids (chub, barbel)	$v < 1.5$ m/s
Big-size fishes like salmonids (salmon, trout)	$v < 2.0$ m/s
Flow parameter	*Size*
Mean velocity	$v = 0.4–0.6$ m/s
Velocities at the fishway mouth	$v < 1.9$ m/s
Velocities at the inlet of the upper water	$v < 1.2$ m/s
Specific discharge	$q > 0.1$ m^2/s
Unitary energy of water	$E < 200$ W/m^3
Geometric parameter of fishway	*Size*
Diameter of used stones	$d = 0.4–0.7$ m
Width of stone baffle	$w = 0.9–1.2$ m
Bottom slope	1:75–1:20
Difference in water levels between chambers	$\Delta h = 0.05–0.15$ m
Width of fishway	$b > 0.8$ m
Length of chamber	$L_{min} = 3 \times L$
	$L > 4.0$ m
Water depth in chamber	$t_{min} = 2.5 \times H$
	$t = 0.2–1.5$ m
Width of slots	$s_{min} = 2 \times D$
	$s = 0.1–0.5$ m
where: D – width, H – high and L – length of fish *[m]* [13]	

Fishways dimensioning based on the above design recommendations should be at the same time, related to the need to adapt them to local conditions prevailing at the construction site of fishway (species composition of fish, terrain, hydrological conditions).

4. ASSESSING THE EFFICIENCY OF FISHWAY

It is important during designing a "close to nature" passage for fish provide a suitable for hydraulic conditions of fish fauna. Mostly, to assess the effectiveness of the functioning of those structures, designers using the data about the maximum velocities of the flow (Tab. 1) and analyzing a stream of water turbulence inside the ladders. Turbulence in a fishway is often estimated by means of the so called *parameter of unitary energy of water E.* This value can be calculated from:

$$E = \frac{\rho \cdot g \cdot \Delta h \cdot Q}{A \cdot t} \;, \quad [\mathrm{W/m^3}] \tag{1}$$

where:
Δh – difference in water levels between chambers [m],
Q – water flow rate in the fishway [m^3/s],
A – chamber (pool) surface area [m^2],
ρ_w – density of water [kg/m^3],
t – filling of the chamber (depth) [m].

For strong fish species which are good swimmers this parameter’s value should not exceed *200* W/m^3, whereas for small fish species, juvenile fish and fry the limit is $E = 100\ W/m^3$.

Unfortunately, often a built of fish-passages is limited only to the directory selection of ladders type. Even in the case when its hydraulic dimensioning is compatible with the required engineering standards, it happens that the effectiveness of fishway is limited. About such cases, alerts inter alia a professional literature in Germany [1, 2, 13, 14], where amount of fishways is disproportionately higher than in Poland. Therefore, in the authors opinion of the publication, to assess the effectiveness of fishway is necessarily needed a spatial analysis of speed distribution inside the ladders and especially stream turbulence. Study of turbulence in fishways are possible on objects in nature (for example to optimize them), using 2D-numerical simulation or physical models in the laboratory. A quantitative measure of the intensity of turbulence is the degree of turbulence *Tu*, which can be set separately for each direction of flow [17]. This value can be calculated from:

$$Tu = \frac{\sqrt{\frac{1}{3}(v_x^2 + v_y^2 + v_z^2)}}{v_{sr,x}^2 + v_{sr,y}^2 + v_{sr,z}^2} \quad , \quad [\ -\ ] \tag{2}$$

where:
v_x, v_y, v_z – fluctuation velocity components [m/s],
$v_{śr,x}$, $v_{śr,y}$, $v_{śr,z}$ – average velocity components [m/s].

5. LABORATORY INVESTIGATION

At the Institute of Environmental Engineering at the Wrocław University of Environmental and Life Sciences was made a hydraulic model research of the flow conditions for a part of seminatural fishway. 3 m-long fishway (scale 1:3) with elements of biotechnical build-up was built in the linear trapezoidal flume with bottom roughness n = 0.012 $m^{-1/3}s$, longitudinal bottom slope J = 12 ‰, width of the bottom b = 0.90 m and 1:1 bank slopes. Adopted fishway configuration shown in Figs. 6 and 9.

In our experiments we used the common reed (*Phragmites communis TRIN.*). Density of the vegetation zones was 577 stems/m^2, representative diameter of the reed was d_P = 5.6 mm and the representative dimensions of the used stones (B-width, H-height, L-length in the direction of flow) were: a) horizontal projection B x L = 176.5 x 97.2 mm; b) vertical cross-section B x H = 176.5 x 66.1 mm.

Fig. 6. Laboratory model of fishway with biotechnical build-up

Tested in the laboratory fishway model with biotechnical building elements is modular construction. Building "close to nature" fishway in the form of a bypass channel, we use modules, which you can duplicate and expand structure at length, depending on your needs.

5.1. Methods and scope of research

Experiments in the laboratory has mainly focused on the measurement of depth and velocity of water flow at the inflicted flow *Q*. Multidirectional instantaneous velocity measurements carried out using electromagnetic probe PEMS type (Fig. 7) 360 points with dimensions of mesh 0.10 x 0.15 m and characteristic points of movement disorders, especially in apertures of fishway.

Depth was measured by water level indicator with a micrometric screw and a cathetometer. Laboratory measurements have been carried out within the following limits of hydraulic parameters:

- stream flow intensity Q = 30-50 dm^3/s
- momentary speeds v = 0-1,00 m/s
- depth of flow h = 0,15-0,22 m

During the conversion the corresponding values from the model to the nature conditions was used an appropriate criterion of hydrodynamic Froude similarity [17].

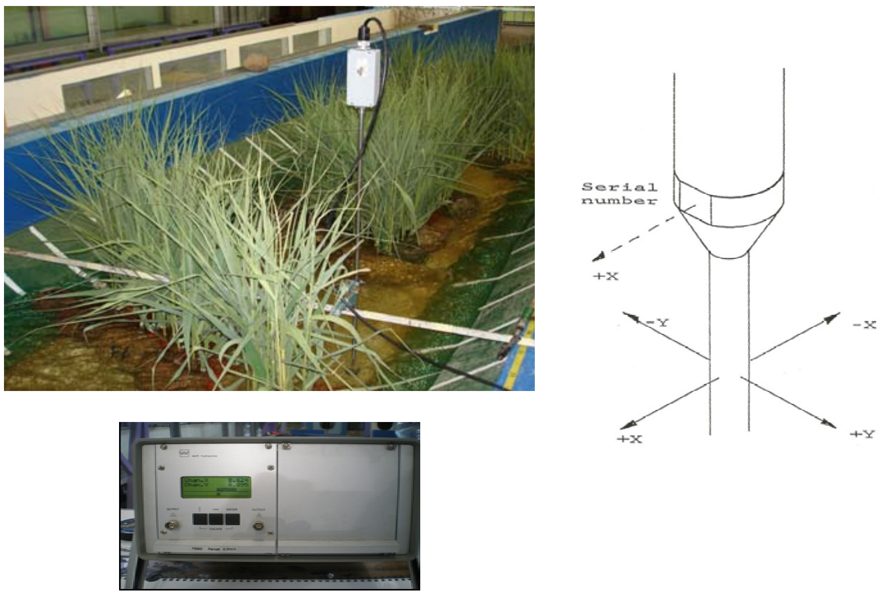

Fig. 7. Measuring instruments (probe PEMS)

5.2. Results and discussion

An example of the results of measurements for discharge Q = 780 dm^3/s (Q_{LAB} = 50 dm^3/s) is shown in Figs. 8-9 and Tab. 2. These data are developed and converted according to the scale (1:3). From the formula (1) set *the unit parameter of water energy E*. You can see that E = 67.80 W/m^3 does not exceed the limit values, even for the young and the weak fish. The same applies to the average flow velocity in fishway (Tabs. 1-2).

Table 2. Example of research results

Lp.	Coordinates of measuring point (Fig.9)		v_i	t_i	t	A	Δh	v_m	E
-	x [m]	y [m]	[m/s]	[m]	[m]	[m^2]	[m]	[m/s]	[W/m^3]
1.	3.60	0.6	1.31	0.630	0.579	20.25	0.104	0.41	67.8
2.	4.20	0.7	0.41	0.585					
3.	5.60	1.0	0.44	0.578					
4.	6.60	1.0	1.36	0.522					

where:
t, A, Δh, E – by formula (1);
v_m - average flow velocity;
v_i - average local measurement points of depth;
x – distance in the direction of the flow;
y - distance perpendicular to the flow (Fig. 9).

However, a full assessment of the effectiveness of fishway is only possible in case of the analysis of the spatial distribution of hydraulic parameters. Laboratory measurements of the velocity field allowed to determine the formula (2) the degree of turbulence *Tu*. Graphic illustration of the turbulence distribution in tested fishway and inside the empty riverbed (for comparison) is shown in Figs. 8-9.

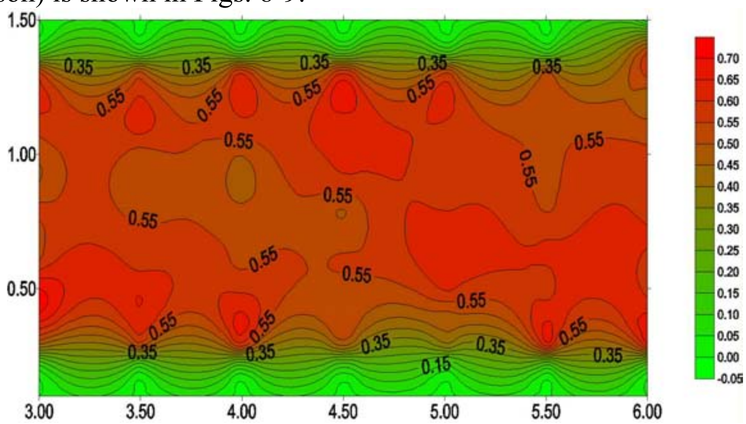

Fig. 8. Distribution of turbulence degree „*Tu*” for empty laboratory flume

Biotechnical build-up affects significantly on the distribution of turbulence in the water stream of fishway (cf. Fig. 8 and Fig. 9). So, it is possible to create a different hydraulic flow conditions inside the fishway e.g. areas of increased turbulence (Tu = 0.5-0.7) and so-called resting areas for upstream fish migration ("the island" on Fig. 9, where Tu = 0.3). This is especially valuable because of the ichthyological requirements [1, 3, 4, 15, 19].

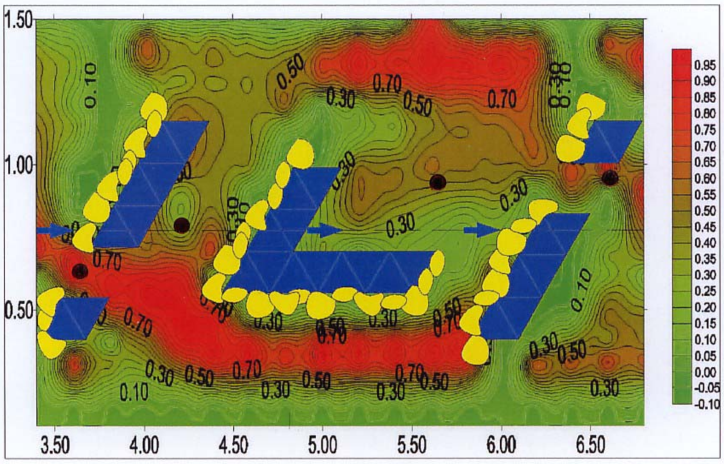

Fig. 9. Distribution of turbulence degree „*Tu*" in fishway with biotechnical build-up (• points of depth measurements)

6. CONCLUSIONS

Biotechnical arrangement (vegetation + boulders) in seminatural fishway is a disorder (obstacle) input to the flow, which results in a reduction of the local velocity and dissipation energy (cf. Fig. 8 and Fig. 9).

Appropriate use of biotechnical arrangement enables to create stable hydraulic conditions for fishway in established parameters, e.g. clear, constant current (Fig. 9) the fish-friendly navigation system in fishways, but also make a rest areas for migratory fish, where the water speed is reduced (Fig. 9).

In order to find for ichthyofauna the optimal deployment configuration of plants and boulders inside the fishway and to evaluation of its efficiency - particularly useful are the spatial structure of hydraulic parameters tests for example. the velocity field or distributions the degree of turbulence *Tu*. Fishways design only on the basis of the average and generalized parameter values *v* or *E* (Tab. 1) does not give complete information about the efficiency of the fish ladders.

The article points out an example of the results obtained for hydraulic research made on the artificial model of fishway in the water laboratory. They represent the output base for further analysis and research. While at the fishways design stage worth recommendations are computer simulations of hydraulic flow conditions e.g. on two-dimensional numerical models.

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BADANIA HYDRAULICZNE DLA POPRAWY WARUNKÓW MIGRACJI RYB - PRZEPŁAWKI „BLISKIE NATURZE”

Streszczenie

W pracy przedstawiono przegląd rozwiązań konstrukcyjnych przejść dla ryb (przepławek) przy obiektach hydrotechnicznych. Modne obecnie i zalecane konstrukcje zmierzają w kierunku rozwiązań „bliskich naturze”. Ich cechą charakterystyczną jest zastosowanie do budowy przepławek naturalnego budulca (kamienie, pnie drzew, żwir, roślinność) w taki sposób, by swoim wyglądem przypominały małe cieki naturalne. Projektowanie hydrauliczne przepławek oparte wyłącznie na kryteriach prędkości dopuszczalnych v_{max} oraz parametru jednostkowej energii wody E, nie daje pełnej informacji o skuteczności działania tych urządzeń. W celu wytworzenia w przepławce optymalnych dla ichtiofauny warunków przepływu przydatne są badania struktury przestrzennej parametrów hydraulicznych np. zaburzeń pola prędkości lub rozkładów stopnia turbulencji Tu. W pracy zaprezentowano przykład takich badań, które autorzy przeprowadzili na modelu przepławki seminaturalnej w laboratorium wodnym IIŚ UP we Wrocławiu. Otrzymane wyniki posłużyły do oceny poprawności funkcjonowania przepławki.