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ANALYSIS OF THE POTENTIAL OF BUILDING RAMPS IN HYDROTECHNICAL STRUCTURES AS A MEANS OF FACILITATING FISH MIGRATION

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Abstract. Measures aimed at preserving "ecological corridors" in rivers are a difficult and complex issue that requires specialized knowledge from many science disciplines. Fishways are one of the most important solutions that ensure the ecological continuity of rivers for fish, particularly due to their near-natural design. A characteristic feature of their construction is the use of natural building materials (stones, tree stumps, gravel, and vegetation) in such a way that their appearance resembles asmall watercourse. The design of hydraulic fishways is based only on the criterion of maximum speed (v_{max}) and the parameter of unitary energy of water E; it does not provide complete information about these devices' efficiency. In order to produce optimal flow conditions for ichthyofauna in the fishway, there is a need for research into the spatial distribution of the hydraulic parameters, such as disorders of the flow velocity field or distributions of turbulence (*Tu*). The aim and scope of this work was to examine the potential of building fish ramps as a means of creating a watercourse through hydrotechnical structures, in order to facilitate fish migration. For this purpose, research was conducted on a physical model in the water laboratory of Prof. Julian Wołoszyn at the Wrocław University of Environmental and Life Sciences. A physical model of a fish ramp was built. Depths and flow speeds at the established water flow rate were measured. Depths of water in the fishway were evaluated in strategic places for fish – i.e. at the entrance and exit of the fishway and between cylindric stones (flow obstacles) on the ramp. The speed was measured at mesh nodes which are spaced at intervals of 15 cm along the length of the riverbed and of 10 cm across the cross section. Maps of the spatial distribution of the flow velocity were drafted based on the results obtained, from which maximum and minimum speeds, stream/current distribution and a rest zone for fish were analyzed. Based on these results it was decided to carry out an attempt to assess the effectiveness of ramps as a means of enabling fish migration.

Keywords: rivers, fishways, fish ramps, flow conditions, model tests

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INTRODUCTION

The subject of the work regards a specific area. All fish migrate for differing reasons depending on the specific needs of individual species. Migration results from a need to change location for hunting, in search of food, and to spawn. Very often migrating fish have obstacles ahead, particularly when it is an upriver migration. They face different kinds of stackings, steps, thresholds, etc. Fishways are structures which maintain biological continuity in rivers. Built on stacking, they enable fish migration up and down a watercourse. A fishway must be designed and constructed so that the upper and lower levels are linked using a concatenation or simple connection (i.e. a ramp). A fishway is a building which eliminates a large local slope of the water table on a longer stretch of river. In a fishway the flow rate of the water should enable upstream migration of aquatic organisms.

Vannote et al. in 1980 formulated the concept of ecosystem continuity [Vannote et al. 1980, FAO/DVWK 2002, Mokwa and Wiśniewolski 2008]. According to Vannote the river is a single ecosystem which changes gradually, along its run, in terms of physical conditions and fertility, and consequently the structure of the flora and fauna changes. Thanks to gradual changes in the abiotic conditions, there arises a specified spatial range of settlement type with appropriate physical and chemical parameters due to which the occurrence of a given species of fish is limited to this area. Dividing the river with hydrotechnical buildings causes an interruption in this morphological continuity, leading to a change in its hydrology, and causing some abiotic factors to change differently than in natural conditions [Radecki-Pawlik 2014, Kałuża and Hämmerling 2015].

Restoring ecological continuity requires an individual approach and a unique solution for each case. Each river, cleaning and hydrotechnical building is an exceptional issue and it is necessary to approach each problem individually. The easiest way to enable fish migration is to build a fishway; however, it is important for it to be efficient and effective. Sometimes before construction of a fishway it is worth considering the point of the given hydrotechnical object. Such consideration is essential due to issues of environmental protection, the biological life of the river, and the conditions and regulations in place [WFD/EC 2000, Wyżga 2013]. Therefore, analysis of the fishways by conducting research on a physical model or on a real object in nature, is also very important.

HYDRAULIC CALCULATIONS FOR THE FISH RAMP

In our laboratory experiments a fishway in form of the block ramp (boulder ramp), which is called a fish ramp, was investigated. In the publication of FAO/DVWK (2002) a method of hydraulic calculations for fish ramps is given. At the beginning of the calculations a water level h was adopted for a given riverbed of known dimensions, as well as stones diameter d_s, and distances between them in the cross section a_y and in the longitudinal cross section a_x. For this filling a field of cross section F was calculated, with wetted perimeter U and hydraulic radius R_h, taking into account the presence of perturbation stones (boulders) in the cross section. The average flow velocity in the fishway was calculated based on the Darcy-Weisbach equation (6).

- Distance between stones – recommendations:
  - Distance between stones (boulders) in the cross section $a_y = (1.5–3) \cdot d_s$
  - Distance between stones in the longitudinal cross section $a_x = (1.5–3) \cdot d_s$
  - Diameters of the stones were assumed based on the publication of FAO/DVWK [2002].
- Volume ratio ε_v

$$\varepsilon_v = \frac{\Sigma V_s}{V_c} \tag{1}$$

where:
ΣV_s – immersed volume of perturbation boulders, m^3,
V_c – total volume of fishway ($V_c = A \cdot L$), m^3,
L – length of fishway, m,
A – unobstructed flow cross-section (without perturbation boulders), m^2.

- Surface area ratio ε_0

$$\varepsilon_0 = \frac{\Sigma A_s}{A_{o,c}} \tag{2}$$

where:
ΣA_s – surface area of perturbation boulders ($A_s = d_s \cdot h$), m^2,
$A_{o,c}$ – total basal area ($A_{o,c} = U \cdot L$), m^2.

- Resistance coefficient of perturbation boulders λ_s

$$\lambda_s = 4 \cdot c_w \cdot \frac{\Sigma A_s}{A_{o,c}} \tag{3}$$

where:
c_w – form drag coefficient of perturbation boulders (c_w = 1,1).

- Resistance coefficient of the bottom of fishway λ_o

$$\frac{1}{\sqrt{\lambda_o}} = -2 \cdot \log \frac{k_s}{14.84 \cdot R_h} \tag{4}$$

where:
k_s – equivalent sand roughness diameter, m,
R_h – hydraulic radius, m.

- Total resistance coefficient λ

$$\lambda = \frac{\lambda_s + \lambda_o (1 - \varepsilon_o)}{1 - \varepsilon_v} \tag{5}$$

- Average flow velocity v_m, $m \cdot s^{-1}$

$$v_m = \frac{1}{\sqrt{\lambda}} \cdot \sqrt{8 \cdot g \cdot R_h \cdot I} \tag{6}$$

where:
- λ – total resistance coefficient,
- g – gravitational acceleration, $g = 9.81$, $m \cdot s^{-2}$,
- I – slope,
- R_h – hydraulic radius, m.

- Maximum flow velocity $v_{\max}$, $m \cdot s^{-1}$

$$v_{\max} = \frac{v_m}{1 - \frac{\Sigma A_s}{A}} \tag{7}$$

where:
- ΣA_s – surface area of perturbation boulders ($A_s = d_s \cdot h$), m^2,
- A – surface area of unobstructed flow cross-section (without perturbation boulders), m^2,
- $v_{\max} < v_{\text{perm}} = 2.0$ $m \cdot s^{-1}$ (v_{perm} – ichtiological highest permissible water velocity).

- Discharge Q, $m^3 \cdot s^{-1}$

$$Q = v_m \cdot A \tag{8}$$

- Froude number Fr

$$Fr^2 = \frac{v_m^2 \cdot b_{sp}}{g \cdot A} \tag{9}$$

where:
- b_{sp} – fish ramp width at water level, m.

The Froude number inside the fishway has to be $Fr < 1.7$ (ichtiological highest permissible value [FAO/DVWK 2002, Mokwa and Wiśniewolski 2008, Kałuża and Hämmerling 2015].

METHODOLOGY OF RESEARCH

Scale of the laboratory model

Assuming that a fish pass is to be used by relatively big and strong fish, the laboratory model should be seen as a fishway at 1 : 7.5 scale. When considering the forces in play in a flow of water through a fishway with boulders (bolts), one might conclude that the predominant factor is gravitation. Other factors (e.g. viscosity) have little influence in this particular case and are negligible. In order to convert the values from the model to the nature and the other way round, one should apply the Froude hydrodynamic similarity criterion suitable for the system [Franzini and Finnemore 1997, Puzyrewski and Sawicki 2000; Sobota 2003]. In an open riverbed three scales were used for examination: geometrical, flow velocity and flow rate. The following Table 1 shows the specifications of the scale model for our experiments, where:

- Geometrical scale S_g:

$$S_g = \frac{L_N}{L_M} \tag{10}$$

where:

L_N – length, width or high in reality, m,
L_M – length, width or high in the laboratory model, m.

- Flow velocity scale S_v:

$$S_v = S_g^{1/2} \tag{11}$$

- Flow rate scale S_Q:

$$S_Q = S_g^{5/2} \tag{12}$$

Table 1. Specifications of scale model

Name of scale	Value
Geometrical scale S_g	7.5
Flow velocity scale S_v	2.74
Flow rate scale S_Q	154.0

Measurement of the water flow velocity

Measurement of water flow velocity was carried out with the electromagnetic gauge PEMS E30. The above probe enables measurement of longitudinal $\pm V_x$ and transverse speed $\pm V_y$ with accuracy to 0.001 $m \cdot s^{-1}$. In order to carry out correct measurements it is necessary to ensure correct placement the gauge, according to markings on the casing of the device [Bajkowski 2010]. The gauging sections were planned at intervals of 15 cm along the length of the riverbed. In each gauging section the speed was measured every 10 cm, in some places, measurements were increased to 5 cm in order to obtain more accurate results.

Area of research

The measuring system consists of a riverbed and a circular overflow. Studies were carried out in an open rectangular riverbed with a concrete bottom. The water on the riverbed passes through the above mentioned circular overflow, which has acute edges, diameter D = 380 mm and well-known hydraulic characteristics $Q = f(H)$. The maximum overflow is 40,70 $dm^3 \cdot s^{-1}$. Next to the overflow a piezometer was installed, which was used to read the water level in the diffusing chamber. The water in the measuring system acts as closed circulatory system. Figure 1 presents a diagram of the measuring system.

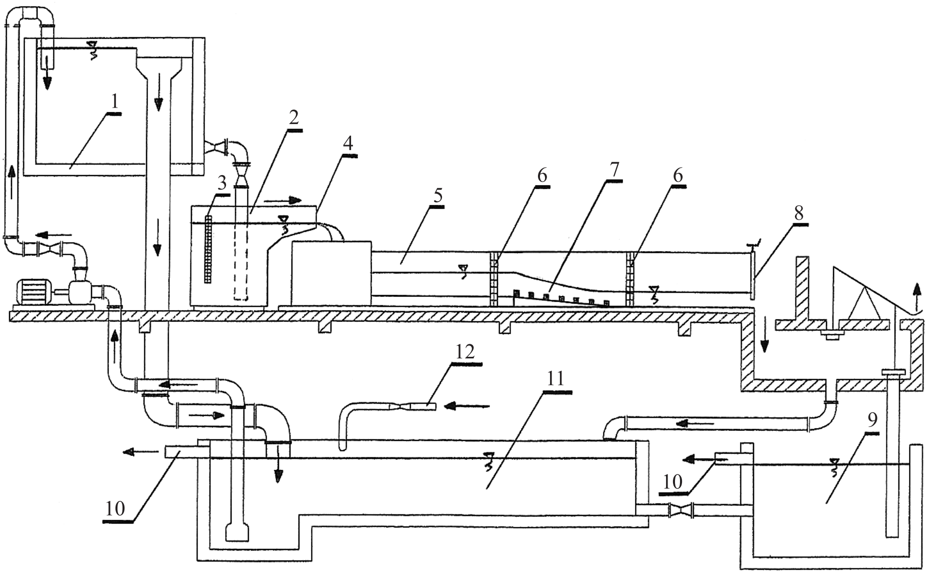

Fig. 1. Schematic view of the measurement set-up: 1 – higher tank, 2 – measuring tank, 3 – gauge, 4 – circular measuring weir, 5 – flume, 6 – piezometers, 7 – fish pass, 8 – weir, 9 – measuring tank, 10 – to sewers, 11 – main tank, 12 – supply pipeline

The fishway model is built from a trapezoid riverbed with roughness on the bottom $n = 0{,}010$, length 10 m, oblong slope $I = 1 : 50$, tilting escarpments 1 : 1, maximum width of the bottom $b_{max} = 110$ cm and minimum width $b_{min} = 90$ cm. The oblong slope was increased by attaching styrofoam plates adapted to the escarpments of the riverbed, and then adding insulation in the form of sealing mortar.

For the purposes of the research a diameter of bolt was selected in the model equal to $d_{s\,M} = 10$ cm, which in fact corresponds to $d_s = 75$ cm. Cylindrical stones (flow obstacles on the ramp) were spaced every 25 cm along the width and length of the model ($a_{x\,M} = a_{y\,M} = 25$ cm – in fact $a_x = a_y \approx 1.9$ m). The cylindrical stones were made of concrete, and cast using a form made of PVC pipe with a diameter of 10 cm and 20 cm. A total of 135 cylindrical stones were made (Fig. 2). Measurements of flow velocity and water levels were conducted for the ramp section. The measuring station for the fishway had a length of $L = 3.60$ m and was located on the section – from 1.25 m to 4.85 m of the riverbed.

Measurements

In the empty riverbed, without bolts or other elements increasing roughness (flow obstacles), measurements were carried out for the flow 33 $dm^3 \cdot s^{-1}$. Next, speeds and water levels were measured. Measurements of water velocity were carried out using the electromagnetic PEMS-type probe [Bajkowski 2010, Mumot and Tymiński 2016]. Measurement accuracy was 0.001 $m \cdot s^{-1}$. Measurements of bi-directional speed points every 10 cm were carried out to the width and 15 cm to the length y in half depths. In the first cross section 4 cylindrical stones were placed, in the second 5, in the next 4, and so on. In total 67 cylindrical stones were arranged on the ramp (Fig. 2).

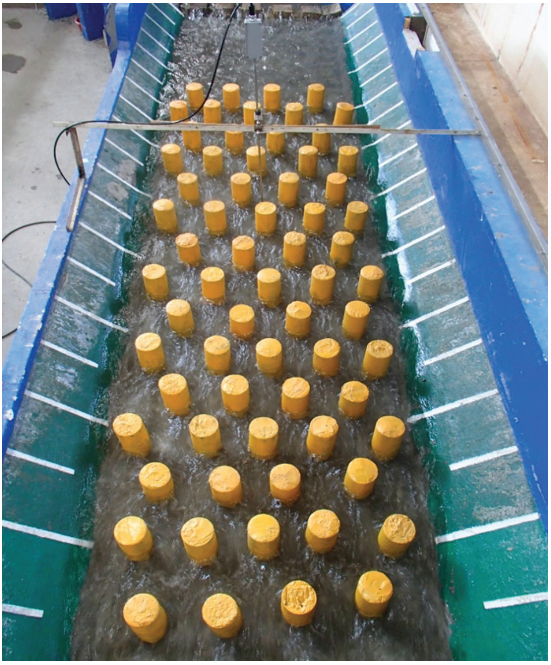

Fig. 2. Diagram showing the spacing of cylindrical stones in fish pass

RESULTS

Empty riverbed

In the empty riverbed, for the flow $Q_M = 33\ dm^3 \cdot s^{-1}$ ($Q_N = 5.08\ m^3 \cdot s^{-1}$), the flow velocity ranged between 1,18 and 0,8, which in fact corresponds to the values 33.22 and 2,18. The highest water velocity was reached at the end of the measuring station. The current of water was unevenly distributed; it is associated with inputting water into the riverbed at an angle. For this reason, the maximum speeds did not appear in the middle of the riverbed, as they would in the case of inputting water parallel to its edges. The results were presented in the form of maps of the spatial distribution of water velocity (Fig. 3) and in tabular form [Tymiński and Kałuża 2013, Tymiński and Mumot 2015]. Depths for this flow were not diversified, and ranged from 3.00 to 3.50 cm.

The flow velocity in a riffle with current $Q_M = 33\ dm^3 \cdot s^{-1}$ ($Q_N = 5.08\ m^3 \cdot s^{-1}$) ranged from $0.01\ m \cdot s^{-1}$ to $0.905\ m \cdot s^{-1}$, which converted for natural conditions, corresponds to a range from 0.03 to $2.5\ m \cdot s^{-1}$. The greatest speed occurred at the end of ramp ($X = 300$–360 cm), where backpressure from the cylindrical stones was absent, resulting in faster drain of water. The lowest speeds were located behind stones, where whirls formed and water velocities decreased to zero. Between stones the flow velocity was equal from $0.3\ m \cdot s^{-1}$ to $0.6\ m \cdot s^{-1}$, which corresponds to a velocity in natural conditions from $0.82\ m \cdot s^{-1}$ to $1.64\ m \cdot s^{-1}$. Depths in this range were from 9 to 10 cm, which in nature is equal from 67.5 to 75 cm.

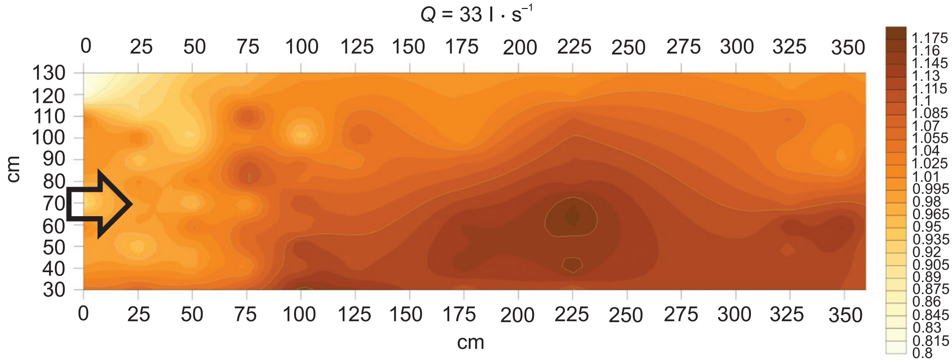

Fig. 3. The spatial distribution of the flow velocity, $\mathrm{m \cdot s^{-1}}$, in the empty riverbed ($Q = 33\ \mathrm{dm^3 \cdot s^{-1}}$)

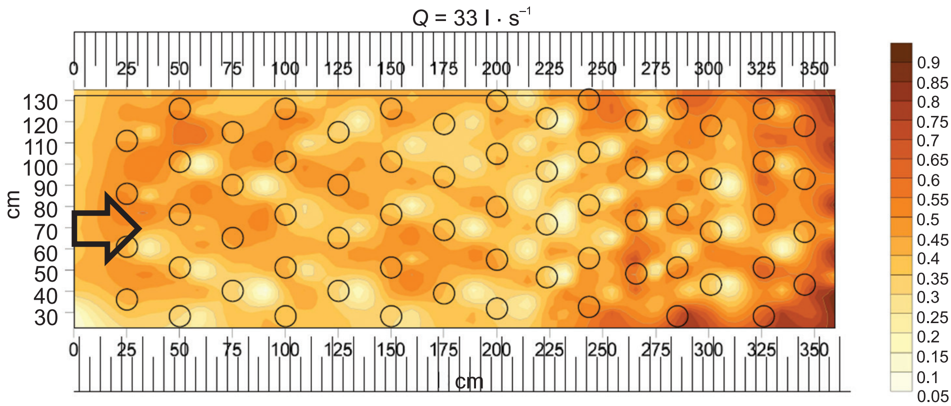

Fig. 4. Spatial distribution of the flow velocity in the fish ramp ($Q = 33\ \mathrm{dm^3 \cdot s^{-1}}$)

Table 2. Filling the fish ramp by flow $Q = 33\ \mathrm{dm^3 \cdot s^{-1}}$

Gauging section cm	Filling cm	Gauging section cm	Filling cm	Gauging section cm	Filling cm
0	9.5	150	10	275	9,5
25	9	160	9	285	10
35	10	175	9.5	290	8
50	10	180	10	300	9
60	8	200	10	310	9
75	9	210	9	325	9
85	9	225	9.5	330	8
100	10	235	10	350	8
110	9.5	245	10	360	5
125	9.5	255	9		
135	10	265	9		

Calculations and flow conditions on the model

The following table (Table 3) presents results measured on the model and converted into real conditions, with calculation of results according to the methodology. For the analysis, we scaled up the results obtained on the model to correspond to the real life conditions of fishways, i.e. filling in the model equal to 9.3 cm corresponds to 70 cm in reality, and the results of the calculations were adapted for such a water level.

Table 3. Results based on the laboratory model versus those calculated (by formulae 1–8) for the fish ramp

Name	H, m		$v_{śr}$, m · s^{-1}		v_{max}, m · s^{-1}		Q, m^3 · s^{-1}	
	Model	Nature	Model	Nature	Model	Nature	Model	Nature
Model	0.93	0.70	0.43	1.17	0.78	2.13	0.033	5.08
Calculations	–	0.70	–	0.98	–	1.97	–	5.09
Model	0.1141	0.86	0.49	1.35	1.00	2.74	0.050	7.7
Calculations	–	0.85	–	0.99	–	1.96	–	6.7

CONCLUSIONS

Based on the studies conducted, it is possible to notice that the speed in the empty riverbed was composed in such a way that a clear water current was visible, which was not even across the entire cross section. This results from the fact that the flowing water in the circuit, before it ran to the riverbed, flowed from the overflow into one tank, then to the next, and then flowed to the riverbed at an angle. Along the entire length of the measuring station, it rebounded from the left edge, and by the end of the station it ran to the right edge. However, this is not a significant error, in the conducted analysis, due to the fact that water also enters the fishway at an angle, which causes an uneven disintegration of speeds. The water flow, with current Q_M = 33 dm^3 · s^{-1} (Q_N = 5.08 m^3 · s^{-1}) qualified as rushing, and speeds exceeded v_M = 1.00 m · s^{-1} (v_N = 2.73 m · s^{-1}). Filling in the riverbed was equal to h_M = 3 cm (h_N = 22.5 cm). The above flow conditions are characteristic of a rift. Placing the cylindrical stones in the pattern of a chessboard resulted in alignment of the speed distribution, i.e. in the entire cross section the flow velocity was similar, as well as the speed distribution along the entire length of the measuring position with a similar arrangement.

Flow conditions for fish were met at the exit of the fishway, as well as in its center. However, at the entrance to the fishway the water velocities were too great, and rebound occurred, therefore in this type of design it is necessary to build a dissipation basin and a sunk exit from the fishway, which requirement can not always be met in smaller tracks or streams. Moreover, at the end of the measuring position (X = 250–360 cm) by the escarpments of the riverbed the flow velocity was higher than in the center. This was caused by slight roughness of the escarpment and riverbed surface. In spite of the fact that water flow velocity was lower than the maximum acceptable, with this configuration of the perturbation stones it was not possible to produce an alluring stream, and speed distribution was very uniform, resulting in a insufficiently varied flow. The result of this may be that the analyzed structure type can be used only by species of fish with good swimming skills, because the average flow velocity for an intensity of $Q_M = 33\ \mathrm{dm^3 \cdot s^{-1}}$ ($Q_N = 5.08\ \mathrm{m^3 \cdot s^{-1}}$) is $v_{śr\,M} = 0.43\ \mathrm{m \cdot s^{-1}}$ ($v_{śr\,N} = 1.17\ \mathrm{m \cdot s^{-1}}$). Small or young fish may have a problem with swimming from the lower water to the upper. The above speeds meet expectations for large (salmonidae) and medium-sized fish (e.g. cyprinidae).

DISADVANTAGES: Increased slope for the above configuration would most probably result in increased flow velocity, which is associated with failure to meet requirements, in terms of flow conditions and potential for fish migration. An additional disadvantage of this design is lack of rest places for the fish; the only places with lower speeds are the places behind stones; however, there are no resting chambers. The solution for the above problem in such a fishway on buildings with large differences between the upper and lower water levels is a design of indirect pools. This solves the problem of rest places for fish, but unfortunately it requires additional space, extends the fishway, and increases its building costs. The scope of flows, at which the ramp operates is quite large, ranging from $Q_M = 7.5\ \mathrm{dm^3 \cdot s^{-1}}$ to $Q_M = 50\ \mathrm{dm^3 \cdot s^{-1}}$ ($Q_N = 1.16–7.743\ \mathrm{m^3 \cdot s^{-1}}$). Another disadvantage is that they need a lot of water, which requirement may not always be met in places, where water is needed for other purposes (i.e. in hydro-electric power stations) or where water resources are not so rich – where low-flows often appear and are quite deep (mountain and foothill streams). Therefore, it is necessary to build ramps instead of fixed thresholds, so that the entire flow passes through the fishway additionally, it is possible to use a multiply split riverbed, where low flows are concentrated in order to obtain the correct water depth for fish migrations.

ADVANTAGES: Their advantage is resistance to sealing and silting up, which is associated with low expenditure on operation. According to the literature [Radecki-Pawlik 2014, Kałuża and Hämmerling 2015], this type of fishway must be controlled after large swells and floods, in order to check the stability of the structure.

The ramp is a good solution to replace fixed thresholds or weirs. It is suitable as a building to restore ecological continuity in mountain, or foothill streams or small watercourses, where species of fish with good swimming skills appear, and hydrotechnical structures have a small slope. Thanks to this, the fishway will have small dimensions. In the case of constructing a fishway with larger dimensions, it is necessary to design places of rest for the fish. In designing the fishway it is necessary to eliminate its defects – lack of rest places for the fish, high speeds or high demand on water – which means that – the ramp was most effective in an endarterectomy watercourse. Additionally, the discussed construction can be used only for the migration of small and medium-sized fish, because it is not possible to create such a configuration so that the distances between riffles with stones are equal to 3 m, as is required in the case of salmon, and at the same time to meet expectations of the flow conditions. Therefore it is important to approach the design individually and analyze all possible aspects, which can affect the effectiveness of the fishway.

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ANALIZA MOŻLIWOŚCI EKOLOGICZNEGO UDROŻNIENIA CIEKU (W PRZEKROJU BUDOWLI WODNEJ) ZA POMOCĄ RAMPY DLA RYB

Streszczenie. Niniejsza praca dotyczy problematyki ciągłości ekologicznej cieków. Bardzo często nie jest ona zachowana ze względu na działania natury antropogenicznej, np. budowle hydrotechniczne przegradzające rzeki. Rosnąca świadomość proekologiczna społeczeństwa, a także regulacje prawne Unii Europejskiej, zobowiązują decydentów do zapewnienia ichtiofaunie rzecznej warunków do swobodnej migracji. Głównym celem przeprowadzonych badań było sprawdzenie możliwość ekologicznego udrożnienia cieku w przekroju hydrotechnicznej budowli piętrzącej poprzez wybudowanie przepławki dla ryb w formie rampy o zwiększonej szorstkości. W laboratorium wodnym im. J. Wołoszyna na Uniwersytecie Przyrodniczym we Wrocławiu wybudowano model rampy dla ryb w skali 1 : 7,5. Elementami do dyssypacji energii strumienia były betonowe cylindry („głazy") umocowane na rampie w odpowiedniej konfiguracji. Wykonano pomiary głębokości i prędkości miejscowych, przy założonym natężeniu przepływu wody. Głębokości wody w przepławce były sprawdzane w miejscach szczególnie ważnych dla ryb – tzn. przy wejściu i wyjściu z przepławki oraz pomiędzy przeszkodami („głazami”). Prędkości przepływu były mierzone w węzłach siatki o wymiarach 15 cm na długości koryta i 10 cm w przekroju poprzecznym. Na podstawie uzyskanych wyników pomiarów sporządzono mapy przestrzennego rozkładu prędkości przepływu, na podstawie których analizowano maksymalne (dopuszczalne ze względu na wymogi ichtiologiczne) i minimalne wartości prędkości, rozkład prądu wabiącego i strefy spoczynku dla migrujących ryb wewnątrz przepławki. Podjęto próbę oceny efektywności działania rampy dla ryb oraz przydatności takiej budowli dla celów migracji ichtiofauny. Przedstawiono zalety i wady badanego wariantu przepławki.

Słowa kluczowe: rzeki, przepławki, rampy dla ryb, warunki przepływu, badania modelowe

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