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Effect of Vegetation on Flow Conditions in the "Nature-like" Fishways

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1. Introduction

Many fish species undertake short or long migrations, which are indispensable for specific stages of their life cycle (e.g. salmon, eel and trout). Hydraulic structures on rivers are often an obstacle that the fish cannot overcome. Another significant issue is that a lot of fish get into power station turbines, which results in a relatively high mortality rate. This phenomenon strongly disturbs the fish population size and the structure of river ichthyofauna. Ecological continuity of river ecosystems is disrupted. Thus, in order to allow the fish life to freely migrate, special fishways are required in the vicinity of hydraulic structures [4, 12].

Research on fishway designs, carried out throughout many years, the efficiency analyses thereof and a better understanding of environmental conditions of ecosystems have allowed for solutions to be found which enable water organisms to overcome hydraulic obstacles in conditions near to natural. "Near-natural" /semi-natural/ designs become increasingly popular and trendy [10, 18, 23]. They include, amongst others, the passes integrated into hydraulic structures such as stone ramps (rapids and ramps) as well as bypass fishways in the form of a channel (Fig. 1a) or a sequence of pools (Fig. 1b). These structures are located away from the main river bed and bypass the dam. It is such bypass fishways with which we are concerned in the present paper.

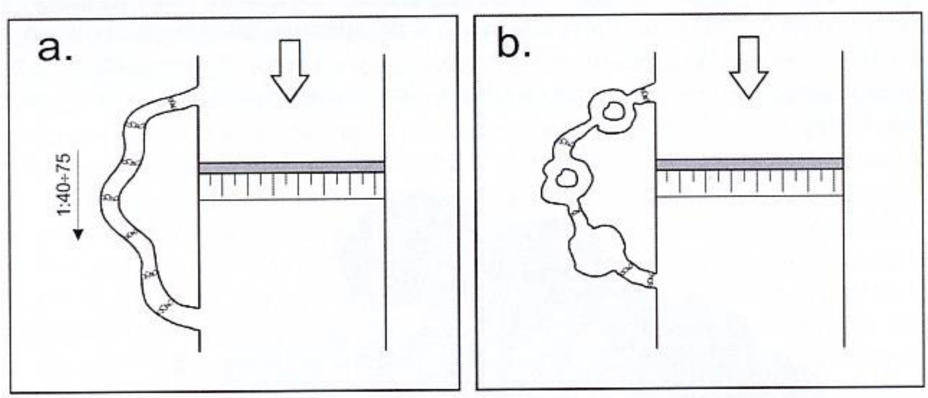

Fig. 1. Types of bypass fishways according to DVWK [5]
Rys. 1. Rodzaje przepławek obejściowych wg DVWK [5]

2. Semi-natural Bypass Fishways

Bypass fishways (bypass channels) resemble mountain streams and creeks. Natural materials such as wood, vegetation, gravel, stones and rocks are used for their construction. They are designed in a unique and individual way for each hydraulic structure. The primary design goals are to provide for all the ichthyofauna needs without hindering the correct operation of the dam and to integrate the fishway, as much as possible, into the surroundings (Fig. 2).

Irregular and varied shape of a fishway makes it resemble a natural watercourse. This is why a bypass should run by a winding channel, using the existing old river bed sections, water-mill channels and ponds. Water bodies integrated into bypass channels are important flow velocity limiters and provide resting places for the migrating fish [13, 18, 23]. These aspects are particularly significant when big level differences occur (of up to 10 m). Another solution which provides the required resting zones for fish is a bypass channel with alternating sections of big and small gradients. Usually, the bypass bed gradient ranges from 1:20 to 1:75 (exceptionally 1:100) [11].

Fig. 2. Semi-natural bypass fishway in the old river bed of the Rhone [7]
Rys. 2. Bliska naturze przepławka obejściowa w starym korycie rzeki Rhone [7]

In bypass fishways of particular importance are the elements of biomechanical build-up. In hydraulic context, the role of vegetated zones and rocks is to appropriately slow down and diversify the water flow velocities and to provide a distribution of turbulence in the fishway which would be appropriate for the migrating fish.

3. Ichthyofauna Requirements and Guidelines for Fishway Design

In the literature of the subject very little information is available on the geometric and more importantly motoric properties of individual fish species. Such information might include any data on the maximum surmountable height, the ability to jump, the admissible time a fish can swim against the current with maximum expenditure of energy or the recommended and maximum values of water velocity in the stream. It does pose a certain problem for the designers, as at the stage of hydraulic dimensioning of fishways some starting assumptions are required. With not enough of detailed data, many simplifications and generalizations must be made. Consequently, in our country's practice, the design guidelines drawn up by a German interdisciplinary expert team [1–6, 13,16–

17] are commonly used. A summary of its key assumptions is given below (Tabs. 1–2).

Table 1. Permissible water flow velocities in fishways [1–6, 13, 15–17]
Tabela 1. Dopuszczalne prędkości przepływu wody w przepławkach [1–6, 13, 15–17]

Type of fish	**flow velocities**
Big-size fishes like salmonids (salmon, trout)	v < 2 m/s
Medium-size fishes like cyprinids (chub, barbel)	v < 1.5 m/s
Small fishes and juveniles	v < 1 m/s
Velocities at the inlet of the upper water	v < 1.2 m/s
Velocities at the fishway mouth	v < 1.9 m/s

Table. 2. Fishway design guidelines [1–6, 13, 15–17]
Tabela 2. Wytyczne do projektowania przepławek [1–6, 13, 15–17]

Parameter	**Size**
Specific discharge	$q > 0.1$ m²/s
Bottom slope	1:75–1:20
Width of fishway	$b > 0.8$ m
Length of chamber	$L > 4.0$ m
Difference in water levels between chambers	$\Delta h = 0.05$–0.15 m
Flow depth	$t = 0.2$–1.5 m
Mean velocity	$v = 0.4$–0.6 m/s
Diameter of used stones	$d = 0.4$–0.7 m
Width of slots	$s = 0.1$–0.5 m

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:

$$E = \frac{\rho \cdot g \cdot H \cdot Q}{A \cdot t}, \text{ [W/m}^3\text{]} \tag{1}$$

where: H – difference in water levels between chambers [m],
Q – water flow rate in the fishway [m³/s],
A – chamber (pool) surface area [m²],
t – filling of the chamber (pool); depth [m],
ρ_w – density of water [kg/m³].

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 $E = 100\ W/m^3$.

4. Modelling Research

4.1. Laboratory fishway model

A novel concept of semi-natural fishway (Fig. 3) has been developed in the Institute of Environmental Engineering at the Wrocław University of Environmental and Life Sciences. Laboratory research has been carried out in a trapezoidal, 15 m-long flume, with 1:1 bank slopes and bottom width of 0.9 m. Flume banks were smoothed out with a finishing cement coat and the bottom was permanently and evenly covered with fine sand with a roughness coefficient $n = 0.012\ m^{-1/3}s$ (according to Ven Te Chow). The flume was supplied from a chamber with a circular weir used for measuring the flow rate Q. At the flume mouth a gate valve was installed for water level control. The research installation was then connected to a circulation water system in the laboratory. Before each measurement series a different variant of a 3 m-long semi-natural fishway was constructed (scale 1:3). This fishway may be seen as a repeatable section of the bypass channel shown in Fig. 1a. The main goal of these experiments was to investigate the hydraulic flow conditions for various configurations of vegetation and stones in the fishway (Fig. 3, 5).

4.2. Biotechnical build-up

In our experiments we used the common reed (*Phragmites australis (Cav.) Trin. ex Steudel*). In order to facilitate fast and repeatable construction of the biotechnical build-up zone in the fishway, custom-made "pots" were used for holding the vegetation. The base modules consisted of triangular stone bases with holes for reed stems. These modules were used to arrange various spatial build-up patterns in the fishway bed. Sample pots are shown in Fig. 4.

Fig. 3. Laboratory model of fishway with biotechnical build-up (Photo T. Tymiński)
Rys.3. Laboratoryjny model przepławki z zabudową biologiczną (fot. T. Tymiński)

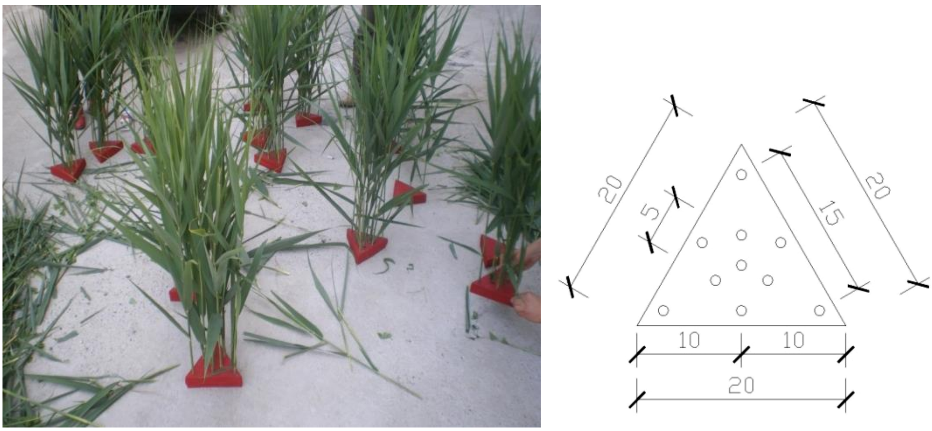

Fig. 4. Pots for vegetational build-up – dimensions of the repeatable element [cm] (Photo T.Tymiński)
Rys. 4. Donice do zabudowy biologicznej – wymiary elementów [cm] (fot. T.Tymiński)

4.3. Investigated fishway variants

The triangular pots with plants and stones were used to form three variants of biotechnical build-up in the fishway: a) Variant 1 (Figs. 3, 5), m = 370 pcs., n = 37 pcs.; b) Variant 2 (Fig. 6), m = 280 pcs., n = 28 pcs.; c) Variant 3 (Fig. 7), m = 320 pcs., n = 32 pcs. (where: m – number of stems of plant elements; n – number of pots for vegetational build-up). Representative diameter of the vegetation (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.

Each of the investigated fishway variants constituted a separate module, which could be extended in length (duplicated).

4.4. Methods and scope of research

The key idea of our research was to look at the biological build-up as obstacles which intensify energy dissipation, result in local swelling and most importantly reduce the velocity of water flow. The hydraulic experiments carried out in a lab consisted in the measurements of depth, flow velocity and stream distribution for a given flow rate Q. Multidirectional measurements of local velocity were carried out by means of a programmable electromagnetic probe PEMS-E30 (with an accuracy of ± 0.001 m/s) at 360 characteristic points of flow disturbance, especially in chambers and stream narrowings (mainly above and below the “gaps”). The measurements of water table were made with a needle level gauge and a cathetometer. Each series of measurements was repeated and results were averaged. Before the experiments the measuring instruments and the flume had been tared. Laboratory measurements were carried out within the following hydraulic parameters range:

- flow rate Q = 30–50 dm^3/s
- instantaneous velocities (at grid nodes 0.10 x 0.15 m) v = 0–1.00 m/s
- flow depth h = 0.15–0.22 m
- constant bottom slope over the whole fishway length I = 12 ‰

An important role was played by the observation and measurements of fish resting zone with reduced water velocity. For the measured flow rate Q, the velocity field and the parameter of unitary energy of water E (formula /1/) were empirically determined and then shown graphically. Both were used as a criterion for operational efficiency of investigated variants of fishways with vegetational build-up.

Assuming that a fishway is to be used by relatively big and strong fish like trout or salmon, the laboratory model should be seen as a bypass fishway segment at 1:3 scale. When considering the forces in play in a flow of water through a fishway with biologic build-up, 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 [9, 14, 21].

5. Research Findings and Discussion

Based on the laboratory measurements, the local velocity spatial distribution graphs (isotachs) have been developed for the investigated fishway variants. These diagrams are shown in figures 5–7.

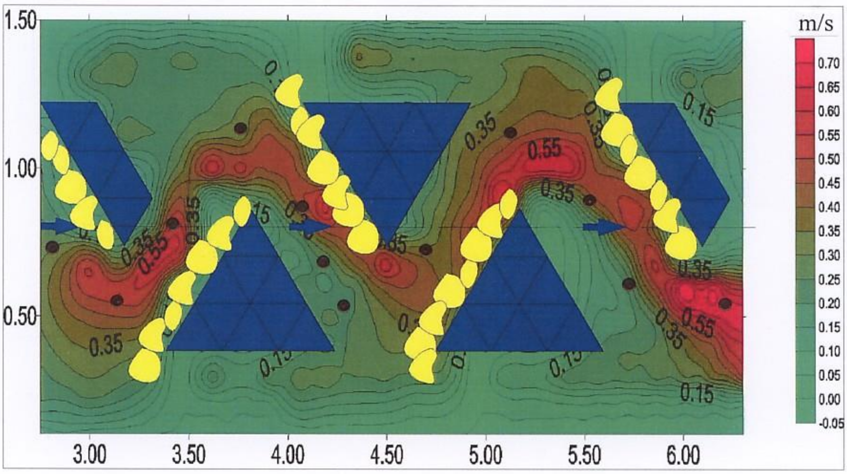

Fig. 5. Local velocity distribution for variant 1(• points of depth measurements)
Rys. 5. Lokalny rozkład prędkości dla wariantu 1 (• punkty pomiaru głębokości)

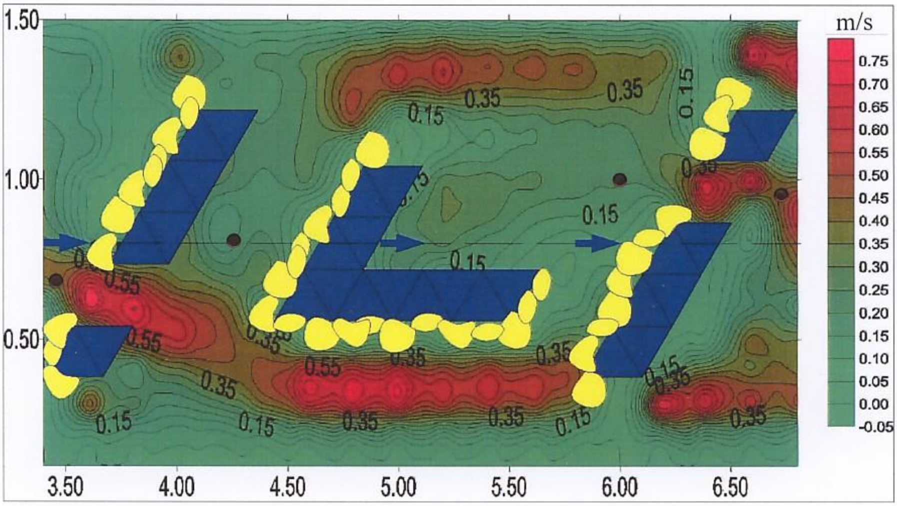

Fig. 6. Local velocity distribution for variant 2 (• points of depth measurements)
Rys. 6. Lokalny rozkład prędkości dla wariantu 2 (• punkty pomiaru głębokości)

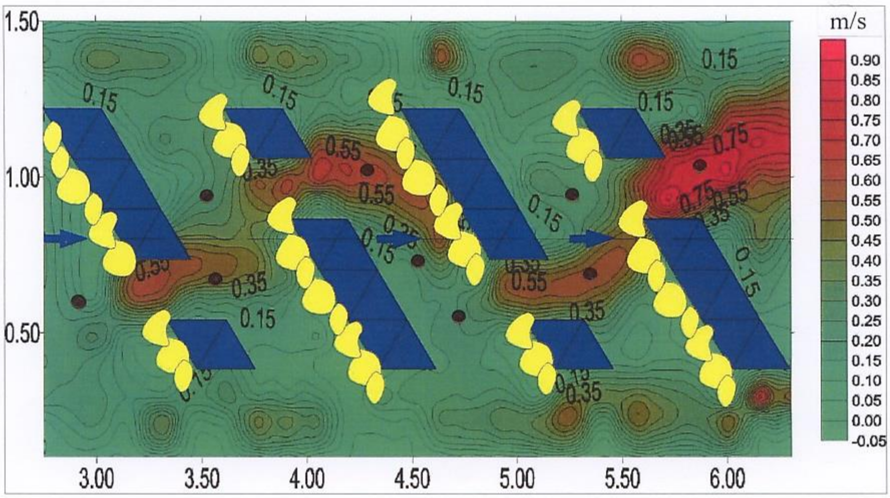

Fig. 7. Local velocity distribution for variant 3 (•points of depth measurements)
Rys. 7. Lokalny rozkład prędkości dla wariantu 3 (• punkty pomiaru głębokości)

The distributions of streams and turbulence in fishways are of particular importance for the ichthyofauna and are often decisive for the operational efficiency of these installations. The attraction currents (the predominating directions of streams) must work together with the fish resting zones, where water velocity is reduced (bright colour in Figs. 5–7). An analysis of velocity distribution in the fishway (Figs. 5–7) has shown that each investigated variant diversifies the flow conditions in a way which is favourable for the fish. In variant 1 for instance (Fig. 5), areas of smaller velocity appear directly behind the triangular deflectors with v_M = 0.15–0.35 m/s, whereas in the main stream the average velocity in the model was v_M = 0.55 m/s (which would translate to v_N = 1.0 m/s in the nature). In each variant a special area was formed by the fishway mouth, where the smallest water depth values (Tab. 3) and the highest flow velocities were measured: $v_{N,\,max}$ = 1.4 m/s for variant 1 ("plant triangles"), $v_{N,\,max}$ = 1.7 m/s for variant 2 ("plant island"), and $v_{N,\,max}$ = 1.5 m/s for variant 3 ("plant baffles"). However, in none of these build-up variants the admissible flow velocity values are exceeded (Tabs. 1–2).

The velocity fields shown for all the 3 configurations of biotechnical build-up unequivocally prove that natural vegetation in a fishway allows for the designer to control the stream of water. Competent vegetational build-up allows for construction of "calm zones" in the fishway, in which fish can rest on their way. Additionally, if stones or rocks are installed in the fishway, their hydraulic impact is even more apparent.

In each of the cases considered the levels of turbulence were the smallest directly behind the obstacles. The highest local velocities were observed in the passage areas (narrows) between chambers. Detailed analysis of these distributions has proved that such increased turbulence will not disturb or hamper the fish migration.

6. Conclusions

Our research has shown that vegetation planted in fishways helps with energy dissipation (E) and reduces the velocity of water flow (v) below the values permissible for the ichthyofauna. Usage of mixed build-up (vegetation + stones) facilitates the development in the fishway of stable hydraulic conditions with assumed parameters, which includes, amongst others, a distinct and constant current to guide the fish through the installation and an attraction current at the fishway entrance, but also the resting zones for the migrating fish. The variant 3 (“baffles”) was found to be optimal for the ichthyofauna. Vegetation build-up in fishways is an interesting alternative for “heavy” technical build-up, but appropriate selection of plant species is essential: the plants must tolerate long periods of submersion in water (e.g. reed).

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Wpływ roślinności na warunki przepływu w przepławkach „bliskich naturze"

Streszczenie

Negatywne dla środowiska wodnego skutki przegradzania cieków budowlami hydrotechnicznymi zrekompensować można budując w ich sąsiedztwie specjalne przejścia dla ryb (przepławki). Współczesne tendencje w konstruowaniu przepławek zmierzają w kierunku rozwiązań „bliskich naturze". Są to najczęściej kanały obejściowe, które swoim wyglądem przypominają potoki górskie lub porośnięte roślinnością małe cieki nizinne. Wykorzystane do ich konstruowania roślinność oraz żwir, kamienie i głazy oprócz redukowania prędkości przepływu, dają możliwość harmonijnego wkomponowania w otoczenie. Przy hydraulicznych obliczeniach takich przepławek ważna jest znajomość wymogów ichtiofauny oraz oddziaływania roślin na strumień, głębokość wody i prędkość przepływu. W laboratorium wodnym przeprowadzono hydrauliczne badania modelowe dla 3 wariantów przepławki o różnej kombinacji rozmieszczenia w niej roślin (trzciny) i kamieni. Dla zadanego natężenia przepływu Q wyznaczono empirycznie pole prędkości oraz parametr jednostkowej energii wody E, które posłużyły jako kryterium oceny skuteczności funkcjonowania badanych przepławek z zabudową biologiczną. Lepszym rozwiązaniem okazało się seminaturalne przejście dla ryb z kamieniami i roślinnością wbudowanymi w koryto przepławki w formie rygli i komór.