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Assessment of migration conditions for fish swimming through a semi-natural fish pass on the Nidzica River in Bronocice

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Abstract: Fish passes are essential elements for maintaining continuity for migrating fish. Without them, fish would be unable to undertake migration to satisfy their basic life needs. These devices must meet a range of requirements related to the size of individual fish pass elements and the hydrodynamic parameters of the flowing water. Despite efforts, it is not always possible to meet these requirements. There are many causes of errors in the design and construction of fish passes, and each case should be assessed individually. The most severe consequence of these errors is the obstruction of fish migrating upstream.

In this study, an analysis of the permeability of a semi-natural fish pass was conducted for fish. This assessment was carried out using two methods. In the first approach, the required geometric dimensions of the fish pass elements were determined based on the dimensions of individuals living in the river channel. In the second approach, the dimensions were extracted from publications dedicated to slot fish passes, as the studied object resembles such a design.

The analysis revealed that the fish pass does not fulfil its intended role. All fish species living in the Nidzica River channel face difficulties in passing through the fish pass, including the brook trout, for which the object is specifically designed. The main errors stem from the design and construction, resulting in exceeded values, primarily in the hydrodynamic parameters, rendering the fish pass impassable. The study also aimed to develop corrective recommendations considering the latest scientific developments.

Keywords: fish migration, Nidzica River, numerical modelling, permeability, semi-natural fish pass

INTRODUCTION

Worldwide, watercourse obstacles disrupt the migration routes of fish species, reducing life cycle success and often wholly eliminating diadromous fish from watersheds (Przybylski *et al.*, 2020). Efforts to mitigate these effects initially focused on developing devices (fish passes, rapids) to assist adult salmonids in overcoming structures blocking access to spawning grounds (Williams *et al.*, 2012). In recent years, efforts have also shifted towards developing these devices for other species (Plesiński, Gibbins and Radecki-Pawlik, 2020; Kiraga, Kozieł and Naliwajko, 2022). Ecological awareness among water construction designers, engineers, and watershed managers is increasing, as evidenced by the growing number of programs aimed at clearing non-functional hydrotechnical structures that could pose an obstacle for migrating fish. A considerable number of renaturation and unblocking projects have been initiated and carried out in Poland alone (Witkowska, Płowens, and Humiczewski, 2013a; Witkowska, Płowens and Humiczewski, 2013b; Durkowski, 2017; Jeleński, 2017; Jelonek and Zygmunt, 2017; Sobieszczyk, 2017; Abersons *et al.*, 2021; Mikuś *et al.*, 2021; Wyżga *et al.*, 2021). Watershed managers, associations, and foundations cooperating with watershed managers or research organisations run these projects. However, despite changes in the approach to water systems and their development and the increasing consideration of the needs of aquatic organisms when performing any work related to

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riverbed construction, there are instances where specific solutions do not yield the expected results. This may result from a lack of understanding of the functioning of the aquatic ecosystem or a lack of appropriate knowledge and difficulties in designing and constructing elements facilitating fish migration (Michalec, 2013; Hämmerling *et al.*, 2017; Radecki-Pawlik *et al.*, 2019; Plesiński, Radecki-Pawlik and Suder, 2020).

While the geometric dimensions of pools and overflows are easy to incorporate into the design of a fish pass, hydrodynamic parameters must be calculated using empirical formulas or numerical modelling, which is particularly useful in the case of fish passes with very complex geometry, such as semi-natural fish passes (Mokwa, 2010; Hämmerling, 2015; Hämmerling *et al.*, 2016; Hämmerling, Kałuża and Walczak, 2017; Plesiński *et al.*, 2022; Plesiński, Radecki-Pawlik and Rivera-Trejo, 2022). Hydrological understanding is also key to properly functioning the fish pass, especially since the variable flow and water table level affect the input and output pool of the fish pass. Insufficient hydrological knowledge can result in an insufficient or excessive amount of water getting into the fish pass, and there is a risk of failing to generate an enticing current that helps fish find the entrance to the structure (Bartnik, Książek and Wyrębek, 2010; Hämmerling and Wierzbicki, 2015). Other threats arising from a lack of monitoring of the fish pass include silting up the inlet with debris carried during flooding or clogging with sediment (Mumot and Tymiński, 2015; Mumot and Tymiński, 2016; Tymiński *et al.*, 2017), and even poaching (Wierzbicki, 2013).

The development of effective fish passes requires not only technical knowledge in the field of hydraulics and construction but also biological knowledge about the behaviour of fish in the face of variable flows, velocities, and turbulence (Rodriguez *et al.*, 2011; Bermúdez *et al.*, 2012; Cao *et al.*, 2021). Only under such conditions can a fish pass be developed that provides optimal conditions for migrating fish. In the absence of biological or engineering knowledge (or both), the development of practical devices will be burdened with a high degree of uncertainty as to the success of the investment (Williams *et al.*, 2012; Silva *et al.*, 2018).

All species of fish migrate to spawning grounds as well as feeding and overwintering sites; some species travel distances of several hundred meters throughout their lives, while others travel several thousand kilometres (Thurow, 2016). Upstream migrations are particularly important for diadromous anadromous fish species such as sea trout or Atlantic salmon, which migrate to mountain and submontane rivers with gravel bottoms for spawning. However, migration to tributaries of larger rivers is also important for rheophilic fish such as dace, asp, gudgeon, etc. Spawning in the upper parts of rivers or tributaries is a way for fish to create optimal conditions for developing hatchlings and fry with a limited predators and an adequate food base (Cowx and Welcomme, 1998). The lack of river continuity was one of the reasons for the extinction of valuable fish species such as the Russian sturgeon or the Atlantic salmon in Poland (Kukuła, Kukuła and Kulesza, 2008; Bylak, Kukuła and Kukuła, 2009; Radtke, Bernaś and Skóra, 2015; Bylak, 2018). In most waters in Poland, stocking is carried out to maintain the populations of certain species, which is a temporary measure. If these practices are discontinued, the species may disappear from the waters again (Mickiewicz, Draszkiewicz-Mioduszewska and Wołos, 2023). The creation of stable fish populations and the restoration of species connections involves a series of renaturation activities that restore both river continuity and spawning sites and activities related to improving water quality (Silva *et al.*, 2018; Stoffers *et al.*, 2022).

We use simple hydraulic models for riverbeds, in which we only calculate the water level during flood or models prepared to dimension simple hydrotechnical structures. If we want to achieve a spatial extent of the flood zone for rivers during flood flow, we must create a 2D hydraulic model. This generalisation to two dimensions is sufficient for the set purpose and is possible for performing numerical calculations over large model areas. The last and most detailed model is the 3D CFD (computational fluid dynamics) hydrodynamic flow model (Ferziger and Perić, 2002; Plesiński, Radecki-Pawlik and Michalik, 2017; Plesiński *et al.*, 2018; Brunner, Savant and Heath, 2020).

In the CFD model, we can very accurately determine the velocity distribution in each of the flow directions (x, y, z), and determine the maximum velocity values and their occurrence in three-dimensional space, which is crucial for complex hydraulic models, where the size of the maximum velocity matters for the efficiency of the water device (Filipczyk and Radecki-Pawlik, 2021).

In fish passages, a key element ensuring the correct operation of the hydrotechnical structure is water depth, velocity value, and the difference in the water level drop between chambers, but also the ability to disperse kinetic energy through the turbulence created in the fish passage chambers (Lubieniecki, 2008). All these mentioned factors affect the proper functioning of the fish passage. Basing the analysis of hydrodynamic parameters on the ability of the fish pass to carry migrating of fish using only empirical formulas, especially objects with complex geometry, may result in incorrect conclusions and incorrect assessment of the fish pass (Sanagiotto *et al.*, 2019). To verify the operation of the fish passage for the above assumptions, it is necessary to use a CFD hydrodynamic model based on the most accurate LES (Large Eddy Simulation) turbulence model (Herrera-Granados, 2022).

The study aims to assess the passability of a semi-natural fish pass in the form of a bypass channel, bypassing the dam located in the Nidzica River in Bronocice village. This analysis was conducted based on the presented optimal geometric and hydrodynamic data for the analysed fish pass, including fish migrating in the Niedzica riverbed, compared with data obtained from 3D hydrodynamic modelling of water flow in the fish pass.

RESEARCH OBJECT

The object of study is a semi-natural fish pass made in the form of a bypass channel, which bypasses the adjacent double-span weir that dams water for energy (Fig. 1). The fish pass is located on the right bank of the Nidzica River at km 32+080 (50°20'37.46"N; 20°21'25.80"E). It consists of 12 basins (according to the project, there should be 13 (Majerczyk, 2020; Grabowska and Kwiecień, 2021)), separated by wooden walls. Slots in the walls are intended to serve as passages for fish between neighbouring basins. The length of the basins is, on average 2.41 m (should be 2.6 m), while the width of the slits is 0.21 m. The bed width of the fish pass is 1.0 m, while the width of the water level in the basins, according to the project, should be 2.2 m. The inclination of the fish pass banks is 1:1. According to the project, the water depth in the

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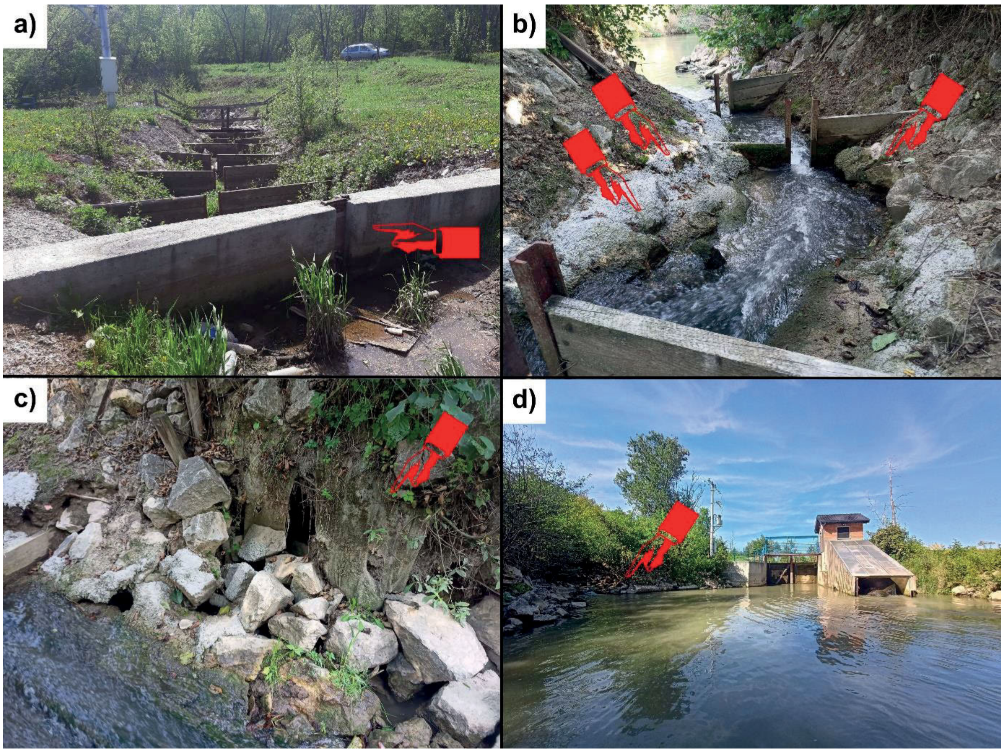

Fig. 1. View of the hydraulic structure complex: a) fish pass – upper part – highlighted closed inlet to the fish pass, b) fish pass – lower part – highlighted bank landslides, c) view of one of the lower basins – highlighted slipped stones with exposed geotextile, d) weir along with the hydroelectric complex – highlighted fish pass outlet, lack of attraction flow, source: own elaboration

basins should be 0.37–0.57 m, while the water level drop between the basins should be 0.19–0.20 m. The minimum flow through the structure (turbine + fish passage) should be $Q = 0.60\ m^3 \cdot s^{-1}$ – this is the inviolable flow. In contrast, the representative flow through the fish pass should be $Q = 0.16\ m^3 \cdot s^{-1}$.

The water-damming weir consists of two gates, each 2.5 m wide (thus, the total weir width is 5.0 m). The ordinate of normal damming is 205.67 m a.s.l., while the ordinate of the lower water level is 202.98 m a.s.l., which gives a difference in water levels of 2.69 m. The minimum and extraordinary damming ordinates are 203.28 and 206.00 m a.s.l., respectively. The throughput of the weir is $Q = 49.4\ m^3 \cdot s^{-1}$. The size of the representative flow is $Q_{1\%} = 71.21\ m^3 \cdot s^{-1}$ (Majerczyk, 2020; Grabowska and Kwiecień, 2021).

The power plant's turbine consists of an Archimedean screw with a maximum flow rate $Q = 2.0\ m^3 \cdot s^{-1}$, a diameter of $d = 2250$ mm, and a power of 40.0 kW with a head drop of $\Delta H = 2.69$ m. The inlet clearance of the turbine is 3.0 m (Majerczyk, 2020; Grabowska and Kwiecień, 2021).

METHODS

FIELD MEASUREMENTS

In 2022, geodetic measurements were carried out using the TOPCON GTS-226 tachymeter. The topography of the fish pass' bed, the size of basins and slots and the distribution of walls separating basins were measured. The geodetic inventory of the fish pass served to depict the current state of the structure along with any structural changes, local scouring of the bed and banks caused by flowing water and human-induced damages resulting from the operation. However, the essential aspect was creating a spatial model of the fish pass, which was subsequently used for numerical modelling. Additionally, the tachymeter was used to measure the water level at the upper and lower positions of the structure, as well as within individual basins.

Hydrodynamic measurements were also performed using the VALEPORT FM-801 current meter. The flow velocity and water level were measured in the basins and slots of the fish pass, as well as upstream and downstream of the structure. These measurements aimed to calibrate the numerical model.

Two measurement stations were established on the Nidzica River, located 500 m downstream and upstream of the Small Hydroelectric Power Plant. These stations were surveyed according to the methodological guide for river ichthyofauna studies by Chief Inspectorate for Environmental Protection (Pol. Główny Inspektorat Ochrony Środowiska) (Prus, Wiśniewolski and Adamczyk, 2016). Fish were captured in the river using an IG-600 device powered by a battery (manufactured by Hans Grassl, Germany), and electrofishing was conducted using pulsed current. The river stations were surveyed by wading up the stream for a 200-meter reach. All fish were measured with a precision of 1 mm and released with due care at the capture site. The entire ichthyofaunal study was conducted in September 2022.

NUMERICAL MODELLING

The following elements are necessary for constructing a CFD (computational fluid dynamics) model: geometry, numerical software, specified boundary and initial conditions, discretisation

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of the hydraulic model, and the turbulent model used. Each of these elements will be described in the following points.

a. Geometric assumptions of the model

The geodetic measurements were processed in Autocad Civil 3D software using the method of point triangulation (Fig. 2). Subsequently, a geometric representation of the channel surface was created, which was then enhanced with walls together with slots. In this way, an accurate terrain model was created, which served as the basis for the later stage as a representation of the flow of water in the turbulent model.

d. Model discretisation and simulation assumptions

Based on the three-dimensional geometry of the measured bypass channel, the hydrodynamic model of the fish pass has been discredited along the entire length of the structure. Due to the variable shape of the fish pass and the desire to limit the number of computational nodes, the computational mesh was divided into five computational grids sewn together by the flow continuation condition.

The calculation aimed to replicate the operation of the fish pass along its entire length with the same accuracy at every point;

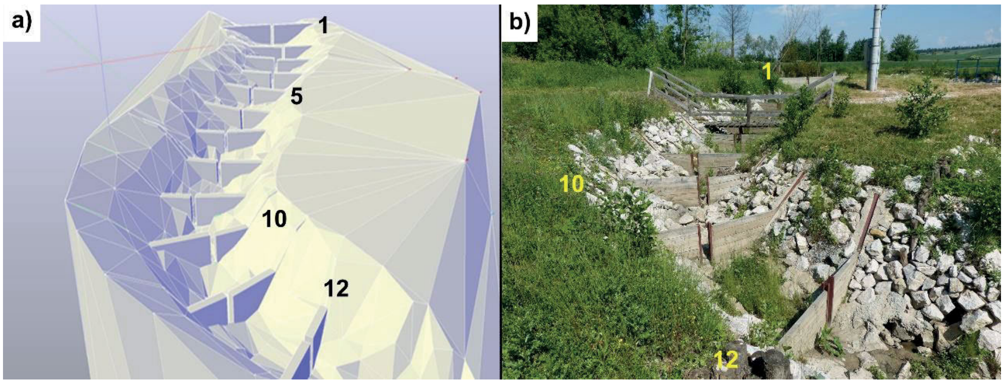

Fig. 2. Geometry of the fish pass: a) model grid, b) real view; walls and slots are numbered; source: own study

b. CFD numerical software adopted

The construction of the CFD model was developed in the Flow3D hydrodynamics calculation program developed by Flow Science Inc. The calculation program was based on Navier Stokes formulas (Eq. 1) (Flaga, Błazik-Borowa and Podgórski, 2004):

$$\frac{\partial(\rho u)}{\partial t} + (u\nabla)(\rho u) = -\nabla p + \mu\nabla^2 u + \rho b \tag{1}$$

where: $u = u_1{\cdot}e_1 + u_2{\cdot}e_2 + u_3{\cdot}e_3$ = flow velocity vector (–), e_1, e_2, e_3 = unit basis vector (–), ρ = fluid density (kg·m$^{-1/3}$), μ = dynamic viscosity (kg·m^{-1}·s^{-1}), t = time (s), p = pressure (Pa), b = mass force vector (–).

The Flow3D software is considered one of the best programs for CFD calculations of free-surface flow, which is determined using the volume of fluid (VOF) mathematical algorithm developed by Hirt and Nichols (1981). Equation (2) prescribes this surface:

$$\frac{\partial(F)}{\partial t} + \frac{1}{V_F}\left[\frac{\partial(FA_x u_1)}{\partial x} + \frac{\partial\left(FA_y u_2\right)}{\partial y} + \frac{\partial(FA_z u_3)}{\partial z}\right] = 0 \tag{2}$$

where: A = fractional areas open to flow, F = fraction function: $F = 0$ = calculation cell is empty; $F = 1$ = the cell is full – the position between these two values defines the free surfaces, the standard value for the surface is $F = 0.5$ = cells on the border between empty and full values, V_F = the volume fraction of fluid in each cell.

c. Boundary and initial conditions

Determining boundary and initial conditions was based on geodetic measurements of the water surface level at the inlet and outlet of the bypass channel. The input condition for the model was the inlet water depth expressed as a water column height provided at a level of 205.67 m a.s.l. The output condition was the water level at the lower position, which was 203.634 m a.s.l.

hence one constant value of the mesh cell height was assumed, with a cubic wall width of 0.03 m. This parameter was selected through iterative calculation by performing multiple numerical calculations, searching for the most optimal mesh size. The initial computational assumption was a 0.2 m mesh; the next computational step was 0.1 m, followed by a mesh at the level of a 0.08 m cell, 0.05 m, 0.04 m and finally, 0.03 m was selected. Below the value of cell width 0.05 m, the results of velocity and depth water values did not change significantly. However, for precise vortex distribution mapping in the LES method, it is recommended that the mesh be as fine as possible. The total length of the bypass channel model is 30 m, the width is 14 m, and the assumed height is about 5 m, with a number of computational nodes of 48,846,520.

The assumed simulation time is approx. 450 s (the process stabilised after approx. 250 s), time step equals about 2.57E-03 s, computational error at the level of 3.58E-03.

e. Turbulent model

In the problem of verifying the fish pass operation, the LES (large eddy simulation) turbulence model developed by Smagorinsky (1963) was taken into account. This method provides a detailed depiction of the vortices generated during the water flows through the fish pass basins.

The LES model is the most accurate tool for numerical calculations. As a result of the performed calculations, we obtain a velocity distribution similar to the real distribution, and the emerging vortices causing the dispersion of kinetic energy reflect the behaviour of water in nature (Lejeune *et al.*, 2022). As with any method of indirect solution of the equation, averages and generalisations must occur. In the LES method, the N-S equations are averaged only at the stage of vortex filtering between the vortices that fit into the grid and the sub-grid ones. The LES model is better than the RNAS model, as it is most often used in hydrotechnical models because the obtained velocity results are

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less homogenised. It is possible to plot the entirety of the phenomenon of water flow through the fish pass chambers (Filipczyk and Radecki-Pawlik, 2021).

Equation (3) for the LES model (Zhiyin, 2015):

$$\frac{\partial(\overline{u_i})}{\partial t}+\frac{\partial}{\partial x_j}\left(\overline{u_i u_j}\right)=-\frac{1}{\rho}\frac{\partial \bar{P}}{\partial x_i}+2\frac{\partial}{\partial x_j}(\mu+\mu_t)\bar{S}_{ij} \tag{3}$$

where: $\bar{P}=\bar{p}+\frac{1}{3}\tau_{ll}$ = modified pressure (Pa), $\mu_t = \rho\left(C_s\bar{\Delta}\right)^2 S$ = eddy viscosity, $S=\left(2\bar{S}_{ij}\bar{S}_{ij}\right)^{1/2}$, $\Delta = (\Delta x\Delta y\Delta z)^{1/3}$ = geometric mean of the spatial mesh size (m), C_s = Smagorinsky's constant (–), Δx, $\Delta y, \Delta z$ = mesh dimensions (m).

DATA ANALYSIS

A variant analysis of the passability of the semi-natural fish pass was performed. In the first variant, the allowable minimum geometric dimensions of individual elements of the fish pass (basins, slots) were developed depending on the dimensions of the fish (DWA, 2014) (Tab. 1). The size of the fish was determined based on the DWA publication (2014), however, this data was matched with the dimensions of the fish caught during field measurements (Tab. 2). The hydrodynamic parameters (flow velocity, water drop, dissipation energy) were determined from several publications (Gebler, 1991; DVWK, 2002; Schmutz and Mielach, 2013; DWA, 2014) for species occurring into the Nidzica River.

Since the bypass channel is styled as a slot fish pass, an additional analysis of passability was performed based on the permissible geometric parameters presented for slot fish passes according DVWK (2002) (Tab. 3).

RESULTS AND DISCUSSION

During ichthyological catches, 125 fish were caught. At the upstream station: 13 brown trouts (*Salmo trutta m. fario*), 14 chubs (*Squalius cephalus*), 13 perches (*Perca fluviatilis*), 4 pikes (*Esox lucius*), 32 roaches (*Rutilus rutilus*) and 5 burbots (*Lota lota*). At the downstream station, the following were caught: 18 brown trouts, 5 chubs, 5 perches, 3 pikes, 10 roaches, and 3 burbots. Figure 3 presents the dimensions of each species caught in the river.

Table 1. Values of acceptable geometrical and hydrodynamic parameters regarding enabling fish migration through "close to nature" hydrotechnical structures

Fish species	$L_{acc,bas} = 3.0\ L_f$	$H_{acc,slot} = 2.0\ H_f$	$H_{acc,bas} = 2.5\ H_f$	$W_{acc,slot} = 3.0\ W_f$	$W_{acc,bas} = 9.0\ W_f$	v_{acc} (m·s^{-1})	Δh_{acc} (m)	E_{acc} (W·m^{-3})
	m							
Brown trout (*Salmo trutta m. fario*)	1.5	0.20	0.25	0.15	0.45	2.00	0.20	160
Chub (*Squalius cephalus*)	1.8	0.32	0.40	0.30	0.9	2.00	0.15	120
Perche (*Perca fluviatilis*)	1.2	0.24	0.30	0.21	0.63	1.50	0.13	100
Pike (*Esox lucius*)	3.0	0.28	0.35	0.30	0.9	1.00	0.08	80
Roache (*Rutilus rutilus*)	1.2	0.26	0.325	0.18	0.54	1.50	0.08	80
Burbot (*Lota lota*)	1.8	0.22	0.275	0.33	0.99	1.00	0.13	100

Explanations: $L_{acc,bas}$ = minimum length of basin (DWA, 2014); $H_{acc,slot}$ = minimum water depth in slot (DWA, 2014), $H_{acc,bas}$ = minimum water depth in basin (DWA, 2014), $W_{acc,slot}$ = minimum width of slot (DWA, 2014), $W_{acc,bas}$ = minimum width of basin (DWA, 2014), v_{acc} = maximum acceptable water velocity (Gebler, 1991; DVWK, 2002), Δh_{acc} = maximum acceptable water drop (Schmutz and Mielach, 2013), E_{acc} = maximum acceptable energy dissipation (Schmutz and Mielach, 2013).
Source: own elaboration.

Table 2. Dimensions of fish species observed in the Nidzica River

Fish species	Dimensions (cm) according to DWA (2014)			Dimensions (cm) according to field measurements			V_{use}/V_{term} (m·s^{-1})
	L_f	H_f	W_f	L_f	H_f	W_f	
Salmo trutta m. fario	50	10	5	50	10	5	1.80/4.10
Squalius cephalus	60	16	10	50	16	10	1.70/4.00
Perca fluviatilis	40	12	7	35	12	7	1.40/–
Esox lucius	100	14	10	75	14	10	0.80/–
Rutilus rutilus	40	13	6	35	13	6	1.30/–
Lota lota	60	11	11	50	11	11	1.00/–

Explanations: L_f = length, H_f = hight, W_f = width, V_{use} = fish useful velocity; V_{term} = fish terminal velocity.
Source: own elaboration acc. to Sakowicz and Żarnecki (1954) and Bartnik *et al.* (2011).

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Table 3. Values of acceptable geometrical and hydrodynamic parameters regarding enabling fish migration through slot fish pass

Fish species	$L_{acc,bas}$	$H_{acc,bas}$	$W_{acc,slot}$	$W_{acc,bas}$	v_{acc} ($m \cdot s^{-1}$)	Δh_{acc} (m)	E_{acc} ($W \cdot m^{-3}$)
	m						
Salmo trutta m. fario	1.9	0.50	0.15	1.2	2.00	0.20	200
Other species observed in the river	3.0	0.75	0.30	1.8	2.00	0.20	150

Explanations as in Tab. 2.
Source: own elaboration acc. to DVWK (2002).

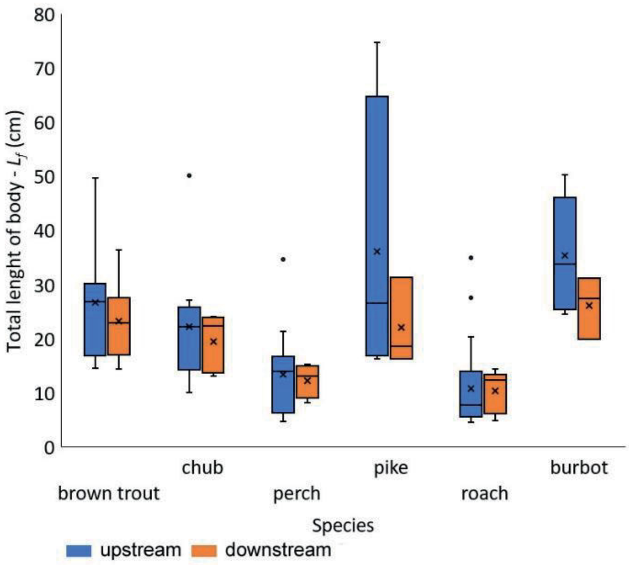

Fig. 3. Length of fish caught in Nidzica River upstream and downstream of the hydrotechnical structure; source: own study

Then, based on the known fish species inhabiting the Nidzica River channel, permissible geometric dimensions and hydrodynamic parameters were determined for the semi-natural fish pass (Gebler, 1991; Schmutz and Mielach, 2013; DWA, 2014). Furthermore, as the analysed fish pass resembles a slot fish pass in its shape and structure, its passability was additionally analysed based on recommended parameter values for this type of fish pass (DVWK, 2002).

The passability of the fish pass was analysed by assessing the geometric (width, length, water depth) and hydrodynamic parameters (velocity, water drop, energy dissipation) of the individual components (slots and basins) of the structure. Numerical modelling was performed for representative flow $Q = 0.16\ m^3 \cdot s^{-1}$ observed at the fish pass.

The slots serve as passages between adjacent basins, ensuring the continuity of the migration route for fish. Their width is significant as if they are too narrow; they can cause difficulties for fish trying to swim into them. Also, due to the flowing water stream's narrowing, excessive water flow acceleration may occur, preventing the fish from passing through the slot. The width of the slots in the analysed fish pass ranges from 0.18 to 0.28 m, with their average width oscillating around 0.20 m. The slots are wide enough for brown trout and roach. However, for perch, some slots are passable, and some are not – the width for this fish species should not be less than 0.21 m. For pike and burbot, the width of the slots is insufficient (Fig. S1).

The water depth is a crucial parameter analysed when assessing water structures' passability. Too low a water depth value is disadvantageous due to the possibility of rapid water flow. Usually, the water depth value in slots is correlated with the velocity of water flow in the slot (low water depth – high velocity, and vice versa, Fig. 4). Meanwhile, in the basins, a high water depth value is necessary to create resting places with relatively low velocities. It is essential to allow fish to gain momentum before making a jump (Larinier, 2002).

The water depth values are relatively high, especially from the third slot onwards (Fig. S2). For the first two slots (counting from the top), the water depth values oscillate around values of

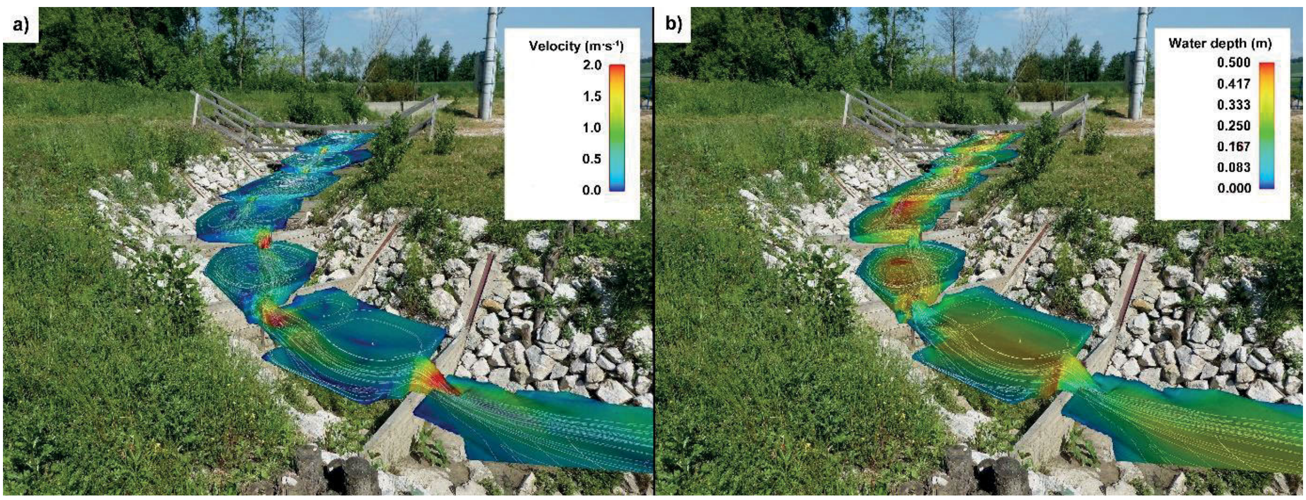

Fig. 4. The result of numerical modelling: a) water velocity, b) water depth; source: own study

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0.25–0.30 m, and then, in the subsequent slots, it reaches values of up to 0.67 m in slots 4 and 5. In the three lowest slots, the water depth values decrease to 0.32–0.39 m. High water depth values in slots 4–9 and the water flow velocities shaping at a level close to 1.0–1.5 $m \cdot s^{-1}$ (these are values not diverging from the sizes observed in other slots) indicate a significant erosion of slot bed occurring at the place. The lowest water depth values were observed in slot no. 2, amounting to 0.25 m. This is a value too low for roach, pike, and chub. Water depth values for chub are also too low at the structure's entrance (slot no. 1).

Too high a flow velocity value can prevent a fish from overcoming a particular element. In that case, the fish is pushed back to the place from where it attempted to overcome the obstacle. The flow velocity in the slots is relatively high (Fig. S3). In the upper slots (No. 1–4), it ranges from 1.0 to 1.5 $m \cdot s^{-1}$. In the middle ones (No. 5–8), it slightly accelerates to 1.5 $m \cdot s^{-1}$, and in the lower ones (No. 10 and 12) it reaches up to 2.0 $m \cdot s^{-1}$. For migrating brown trout and chub, it can be stated that the velocity in the slots should not stop their migration, despite their high values in slots 10 and 12. These slots are at the beginning of the migration route, so brown trout and chub should overcome these places. The situation looks worse for the remaining fish species. For perch and roach, the water flows too quickly in three slots, and in two, it is at the limit of acceptability. For pike and burbot, we observe too high flow velocity values in all slots.

The water drop between basins is a significant parameter that can limit the number of fish passing through. Too high a value makes it impossible for the fish to jump from a lower basin to a higher one (Larinier, 2002). For brown trout, the water drop is too high in slot 11 (Δh = 0.29 m), and the values in slots 1 and 12 are relatively high, almost 0.20 m. Since brown trout is a species that can make the highest jump, the water drop will also be too high for other fish species living in the Nidzica riverbed (Figs. S4, S5).

Basins in fish passes are a significant element of the entire structure – they serve as resting places where fish should rest before attempting further upstream travel. The water depth in the basins should be relatively high and the velocity rate low. Such flow conditions guarantee that the fish can rest before overcoming the next slot.

The width of the basins is sufficient for all fish species observed in the river (Fig. S6). Almost all basins are close to 2.0 m wide or slightly wider. The narrowest is the lower basins (no. 11 and 10) – their width is 1.7 m and 1.4 m, respectively, which is still an acceptable value. The length of the basins, ranging from 2.3 to 2.6 m, is sufficient for most fish species, except for pike, for which the basin dimension should be at least 3.0 m (Fig. S7).

In the analysed fish pass, the water depth presented in Figure S8 shows values in the upper, middle and lower parts of each basin in the mainstream. The water depth in many places is too low for all fish living in the riverbed. Attention should be paid to the upper parts of the basins, where the water depth values are lower than in the middle or lower parts of the same basin. This situation is encountered in basins no. 1, 2, 3, 5, 7, 10, 11, and 12. This is related to the water flowing through the slots, where the narrowed water stream accelerates, often creating a local hydraulic jump. The flow velocity in the upper parts of the basins, just below the slots, is higher or similar to the values in the slots (we observe this situation below slots no. 1, 11, and 12). We, therefore, have a situation where the water flows quickly, reaching a value of 2.0 in basins no. 11 and 12, and 2.4 in basin no. 1. Such high water velocities are definitely above the acceptable norms for all fish species living in the river (Fig. S9).

A significant hydrodynamic parameter that can prevent fish migration through a fish ladder is energy dissipation from the flowing water (Enders, Boisclair and Roy, 2003; Wyrębek and Florek, 2015). It is proportional to the amount of flowing water and the drop height and inversely proportional to the volume of the basin into which it falls. Thus, the greater the intensity of water and the greater its drop, the greater the energy is produced, which can be dispersed in the damping basin (the larger the basin, the greater the efficiency of energy dispersion). In the case of the analysed fish pass, very high values occur in the highest basin no. 1 (E = 260 $W \cdot m^{-3}$) and the three lowest, no. 9, 10, and 11 (E = 179, 291, 417 $W \cdot m^{-3}$ respectively). These values are significantly too high, causing none of the individuals of the species observed in the river will be able to overcome this structure. In basin no. 1, it should be noted that a high value of energy dissipation is determined by a high water drop (Δh = 0.19 m) in correlation with low water depth (h_{avg} = 0.17 m). In basin no. 9, the water drop increases, but the basin volume decreases. In basin no. 10, its small volume is observed (V_o = 0.50 m^3), while in basin no. 11, there is a high water drop (Δh = 0.29 m) (Fig. S10).

Table 4 specifies the number of non-passable basins and slots that do not meet the proper parameters, and Figure S11 illustrates the permeability of individual elements of the fish pass.

Analysing the passability of the examined structure based on standards for slot fish passes, it appears that the fish pass is also blocked for all species living in the Nidzica riverbed. Analysing the slot width, they are sufficient for brown trout but too narrow for other species. The width of the basins for brown trout is within the permissible dimensions (W_{min} = 1.4 m), while for other species, the two lowest basins, which are constricted, no longer meet this criterion (W_{min} = 1.8 m). The length of the basins for brown trout is sufficient, but for other fish species, it is too short. In turn, the water depth in the basins is too low for every fish species. For brown trout, it should be at least 0.50 m and for other species, 0.75 m – these values are sporadically achieved, locally and only in the deepest parts of the basins.

A semi-natural fish pass should reproduce the natural watercourse as faithfully as possible, which will run around the obstacle. The ideal solution would be to design and build this type of facility so that it is not only a migration route for fish but also a habitat and a place of life (Jungwirth, 1996; Meulenbroek *et al.*, 2018). The research shows that the fish pass is not a passage for migrating fish. To fulfil its tasks, the fish pass should undergo the following procedures:

1. To reduce the velocity of water flow in slots and just below them, the simplest solution seems to be to increase the width of the slots. Such a solution can not only slow down the flow but also diversify it, which is particularly recommended for structures that should allow the migration of many species – each of them then has the opportunity to choose the most appropriate route (Quaranta, Katopodis and Comoglio, 2019; Wiegleb *et al.*, 2023). A consequence of increasing the width of the slots may also be an increase in the volume of water flowing, which may cause difficulties in maintaining the appropriate water level (and thus depth) in the basins. Therefore, the most reasonable solution seems to be to repair the erosions in the

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Table 4. The number of non-passable elements serves as barriers for individual fish species

Fish species	$L_{acc,bas}$	$H_{acc,slot}$	$H_{acc,bas}$	$W_{acc,slot}$	$W_{acc,bas}$	$v_{acc,bas}$	$v_{acc,slot}$	Δh_{acc} (m)	E_{acc} ($W \cdot m^{-3}$)	*P* (%)
	m					$m \cdot s^{-1}$				
Salmo trutta m. fario	0	0	5	0	0	1	0	1	4	B: 45% S: 8%
Squalius cephalus	0	3	11	12	0	1	0	3	6	B: 100% S: 100%
Perca fluviatilis	0	0	5	6	0	2	3	6	6	B: 54% S: 50%
Esox lucius	11 *0	1	10	12	0	2	12	8	7	B: 100% S: 100%
Rutilus rutilus	0	1	8	0	0	2	3	8	7	B: 73% S: 66%
Lota lota	0	0	5	12	0	2	12	6	6	B: 54% S: 100%

Explanations: *P* = the percentage of unobstructed basins and slots for fish migratory, B = basins, S = slots, * = taking into account the dimensions of fish measured while fishing in the Nidzica River, other symbols as in Tab. 1.
Source: own study.

bed, which occur just below the slots. The repair can be performed in the form of the installation of rough elements in the bed of slots and basins, such as brushes, which successfully disperse the kinetic energy of the flowing water and slow down of water (Kucukali and Hassinger, 2020; Kucukali, Alp and Albayrak, 2023). In addition, they are an ecological element that does not create additional stress for fish. In addition to brushes, research has also been conducted on cylindrical elements (Sanagiotto *et al.*, 2019; Ahmadi *et al.*, 2022).

2. It is also necessary to level the bed by filling in the holes that appear in the place of the scours and restoring the designed drop between the basins. This would reduce the drop in the water surface between adjacent basins and consequently reduce the flow velocity (White, Harris and Keller, 2011). In case of no improvement in the passability of the fish pass, it is worth considering building two additional basins at the end of the fish pass.
3. It would be advisable to increase the opening at the inlet of the fish pass and lower the bed at the inlet, which would improve the amount of water flowing to the remaining basins, increase the depth of the water in the basins, and reduce the velocity and energy of dispersion. Also, the level of the water mirror under the fish pass should be higher, as also shown in the technical project (Majerczyk, 2020). These solutions would improve the arrangement of the water level not only in the extreme basins but mainly in the middle ones by increasing the depth.
4. The technical condition of the fish pass is only sufficient (Sieinski and Śliwiński, 2015). In places, it has undergone significant degradation, despite its young age. Particularly in the lower basins, removed bank material can be seen. Despite the general aesthetic appearance, the manager or owner does not monitor the fish pass, and the damages are not repaired. This would likely help maintain better technical conditions and improve fish migration conditions. Therefore, a general renovation of the fish pass should be carried out by improving the technical condition of the partitions and removing silt and disconnected material from the fish pass basin slopes.
5. The next significant phenomenon that can affect the efficiency of fish migration is an attraction flow, essentially a signpost aimed at directing migrating fish towards the fish pass. Thanks to it, fish should be able to find the entrance to the fish pass. In the absence of an attraction flow, migrating fish often bypass the fish pass (only a tiny part of them find the entrance to the fish pass, which can instead be a coincidence than an intentional action of the fish), flowing towards the dam (Kopecki, Schneider and Hägele, 2022). To talk about the presence of an attraction flow, the velocity of water flowing out of the fish pass should be 10–20% higher than the average velocity in the river bed (Wiśniewolski, Mokwa and Ziola, 2008). On the other hand, Gisen, Weichert and Nestler (2017) say that it is enough for the water to flow out of the fish pass just 5% faster than it flows in the river bed. The attraction flow in the studied fish pass was analysed only based on field measurements. Hydrodynamic measurements measured the velocity of water flowing out of the fish pass and the velocities of water in the river bed below the weir in various hydrological conditions. In each case, the attraction flow never occurred even in low water conditions in the river. The stream of water from the Archimedes screw continuously flowed faster than the one coming out of the fish pass, directing fish towards the power plant. This poses an even greater problem as the power plant is opposite the river to the fish pass. A relatively simple solution may be installing grates, electric barriers, or even solutions involving both technologies (Mokwa, Kasperek and Wiśniewolski, 2007; Lemkecher *et al.*, 2021; Haug *et al.*, 2022).

Implementing the above recommendations will bring the best effect if the facility is thoroughly modernised considering all the above recommendations. Nevertheless, our orders should be subject to further analysis along with the development of the fish pass redevelopment concept. Implementing only one recommendation may bring only a partial and probably short-term effect.

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CONCLUSIONS

The analysed fish pass is a so-called bypass channel for fish, made in the form of basins separated by walls, in which slots provide continuity of flow. Two publications were used for the analysis. One of them bases its boundary values on the dimensions of fish passes elements based on conversions from the morphological data of individual fish species. The other publication presents data for slot fish passes. In both analyses, it follows:

1. The fish pass is impassable for all fish living in the Nidzica riverbed because:
   a) for brown trout: the water depth in the basins is too low; a high value of water drop was observed between adjacent basins; the dissipation energy is too high; 45% of the basins and 8% of the slots may be an obstacle for migrating fish;
   b) for chub: all basins are too shallow, and all slots are too narrow; some slots also have too low water depth and too high water drop; the dissipation energy is also too high; 100% of the basins and slots may be an obstacle for migrating fish;
   c) for perch: hydrodynamic capabilities are falling; a lower velocity value in the slot is required; in three slots, the water flows too fast; we also observe restrictions due to not meeting the required water depths in the basins and the width of the slots; 54% of basins and 50% of fish pass slots may be an obstacle for migrating fish;
   d) for pike: it's a relatively large fish; hence the requirements for the size of basins and slots increase; each of the basins is too short for the dimensions shown in the publication; however, smaller individuals are found in the Nidzica riverbed – then the basins meet the minimum length requirement; however, the minimum requirements for water depth in the basins, the width of the slots and, in one case, the width of the basin are not met; pike is a poor long-distance swimmer, so the water flows too fast in all slots; the water drop and dissipation energy values in half of the existing elements are too high; 100% of basins and slots may be an obstacle for migrating fish;
   e) for roach: there is too high a water drop between basins on half the number of slots; in half of the basins, the dissipation energy is not sufficiently dispersed, and the water depth is too low; in three slots, the water flows too fast; 73% of basins and 66% of fish pass slots may be an obstacle for migrating fish;
   f) for burbot: primarily, the slots are a barrier to migrating burbots; all are too narrow, and the water flows through them too quickly; also, there is too high a water drop in several slots; in several basins, insufficient dispersion of water energy and too low water depth were observed; 54% of basins and 100% of fish pass slots may be an obstacle for migrating fish.
2. According to the publication presenting data on the required dimensions of a slot fish pass, the analysed structure is also impassable.
3. The fish pass was designed and constructed for brown trout; for this species, the least components of the fish pass (slots and basins) pose a barrier. The geometric dimensions of the basins and slots are in accordance with the recommendations. Only hydrodynamic parameters, such as velocity, water drop, and dissipation energy, are unacceptable, resulting from incorrect design and execution of the fish pass.
4. The analysed structure is part of a water stage located on the Nidzica River. It consists of a fish pass, a weir that raises the water level, and a small hydropower plant equipped with an Archimedes turbine. Designing such a complex water assembly, advanced hydraulic analyses are necessary, taking into account the proper water breakdown into individual structures, appropriate power supply to the hydropower plant, inviolable flow, and appropriate flow for the fish pass. Traditional hydraulic analyses based on empirical formulas, such as Bernoulli's equations or Kirchhoff's laws, do not consider all the difficulties associated with this complicated project. It is necessary to use three-dimensional analysis to consider all the intricate aspects related to the nature of water flow. Unfortunately, as a result of a simplified analysis, the fish pass was designed in a way that does not meet technical requirements and does not consider the behavioural needs of fish, which is inconsistent with the principles of good technical practice. Surprisingly, despite being commissioned in 2015, considering environmental guidelines, the fish pass already requires a complete overhaul. To avoid such problems in the future, proper supervision of the construction process and investment in proprietary oversight is important. Ecological awareness among designers and constructors is growing, which should contribute to implementing more sustainable hydrotechnical, durable, and environmentally compliant solutions.

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at https://www.jwld.pl/files/Supplementary_material_Plesinski.pdf.

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