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REDESIGN OF AN INTAKE FISH PASS STRUCTURE

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Abstract

The article describes the process of redesigning the intake structure of the fish pass at the Žilina water structure in Slovakia. The existing intake structure does not meet the passability requirements for the target species of migratory fish. A design utilizing intake windows at various levels that cover fluctuations in the water level in the reservoir, which has been successfully used for other water structures, has been proposed. The new design was subjected to hydraulic calculations and simulations in the HEC-RAS 2D, 2D numerical model in order to achieve the required parameters such as the discharges, depths, and velocities within the limits for the specified fish zone.

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Key words

- Fish pass,
- HEC-RAS 2D,
- Hydraulic parameters,
- Water intake,
- Velocity field,
- Depths.

1 INTRODUCTION

As a member of the EU, the Slovak Republic, is committed to making migration barriers passable (Directive 2000/60/EC), as is the case with other EU member states (Mader et al., 2020; Slavíková et al., 2020). This applies not only to the construction of new fish passes, but also the improvement of existing ones according to the latest knowledge and research (Directive DVWK 232/1996; Polák et al., 2015; Ocvirk et al., 2020) to meet the ecological requirements of the existing ichthyofauna.

The most significant problem in the passing of fish, either upstream or downstream, is attracting fish into the fish pass facility (Armstrong et al., 2020; O'Connor et al., 2017). The problematic sections are mostly the entrance (for upstream migrants) and the exit into the upstream water. For the entrance, it is recommended to locate it on a side of the hydropower plant close to the barrier and providing it with an additional attractive flow (Armstrong et al., 2020). The exit must also usually ensure the operation of the fish pass through a wide range of the water levels in the reservoir according to the operation of the water structure. A solution to these problems can be as follows: the upper pool can be used to adjust different headwater levels, while a second pool can be used to fine-tune the flow. On the other hand, a discharge control should be possible for the inflow, but for level fluctuations of 0.5 – 1.0 m, a vertical intake slot seems adequate; however, if the level differences are higher, several inflows with flow control functions should be included, as was used at the Váh cascade in Slovakia (Fig. 1) in the 1950s. The lateral positioning of the exit is also recommended, since this can lead any floating debris to bypass the entrance and also help to ensure that it is washed downstream during the cleaning process (Armstrong et al., 2020; Schmutz and Mielach, 2013).

2 MATERIALS AND METHODS

2.1 Description of the locality

The fish pass of the Žilina water structure on the Váh River (Fig. 2) was put into operation in 1998. It is unique in its length, i.e., 9 km, while overcoming a head of 25 m (Žilina, Váh basin, 2022). For the first time in the history of the Slovak Republic, an Environmental Impact Assessment (EIA) process was applied to this structure. Regular ichthyological monitoring, which has

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Fig. 1 *The Váh cascade – the Drahovce water structure, inflow windows at different levels with control gates (photo from 2007, when the reservoir was empty)*

confirmed the occurrence of more than 30 species of fish, is carried out there; the most numerous species include: the common bleak (*Alburnus alburnus*), stone loach (*Barbatula barbatula*), barbel (*Barbus barbus*), common gudgeon (*Gobio gobio*), European chub (*Leuciscus cephalus*), and Eurasian minnow (*Phoxinus phoxinus*). The Váh River in this section is a typical foothill zone river, where there are fish of economic importance, as well as fish in the vulnerable category, which are included on the red list of fish in Slovakia with a special emphasis. The Váh River has a high diversity of species in this location; rheophilic (current) species logically predominate, as it is located in the upper part of the river (Čubanová and Rumann, 2018).

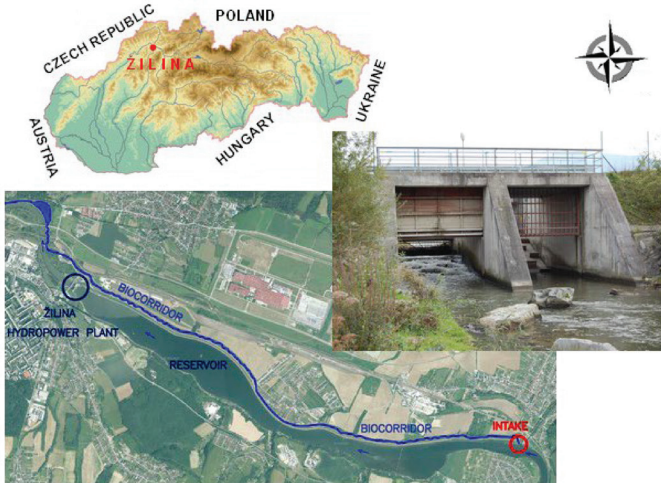


Fig. 2 *Map of the Slovak Republic with the area of interest – the fish pass of the Žilina water structure on the Váh River; the original intake structure is on the right*

2.2 Requirements according to the current regulations

The design parameters of the fish pass on the Žilina water structure at the time of its design were as follows (Čubanová and Rumann, 2018):

– a length of approximately 10 km,
– a trapezoidal cross section; the width at the river bed is 5 – 7 m,
– a water depth of 1 m,
– an operational flow rate of 2 $m^3 \cdot s^{-1}$,
– a flow velocity of 0.6 – 0.9 $m \cdot s^{-1}$ (maximum 1 $m \cdot s^{-1}$).

The riverbed itself meets passability requirements (O'Connor et al., 2017; Polák et al., 2015); the problem is the two-field intake structure. It is an automatic control gate with a flat sliding surface, i.e., a moving ramp (it is on its right side in Fig. 2), which must adjust to changes in the water levels in the reservoir according to the operations on the water structure. This structure is not very passable for the migrating ichthyofauna (the flow velocities exceed the limits); in addition, its functioning is strongly affected by its nearby confluence with the Varínka stream. Another problem that has emerged during the operation of this fish pass is at the outflow (for upstream migrating fish, this is the entrance to the fish pass), which is too far from the barrier itself. Moreover, for the fish, it is difficult to find it. Therefore, a redesign and reconstruction of the fish pass was proposed for these problem areas. The paper deals with the redesign of the existing intake structure.

According to updated ichthyological requirements in the valid Decree (Decree 383/2018) and the Methodological Guidelines (Polák et al., 2015), the barbel fish zone with an occurrence of Danubian salmon was selected as the target fish zone, with respect to the following fish species: the common barbel (*Barbus barbus*), nase (*Chondrostoma nasus*), East European bream (*Vimba vimba*), chub (*Leuciscus cephalus*), dace (*Leuciscus leuciscus*), bleak (*Alburnus alburnus*), grayling (*Thymallus thymallus*), and trout (*Salmo trutta*). According to the State Nature Conservancy of the Slovak Republic, passability is also required for the potential presence of Danube salmon (*Hucho hucho*) and protected low-skilled fish species. The focus of future monitoring will be on the mentioned fish species (after the reconstruction of the fish pass intake structure and its problematic parts).

The limit parameters recommended for a barrier-free fish pass in the barbel zone (Polák et al., 2015) are:

– a velocity of 1.2 $m \cdot s^{-1}$,
– a minimum depth of 50 cm,
– a minimum width at a water level of 5 m,
– a longitudinal slope of 1:70 – 1: 100,
– a resting pool after overcoming a head of 2 m,
– a chessboard layout of single stones (resulting in a sequence of spillovers and pools) protruding 30 – 40 cm above the riverbed bottom,
– good lighting and riparian planting.

2.3 Numerical simulations

The new intake structure is designed as a number of windows in the intake wall at various height levels (Fig. 3); it will be connected to the fish pass by a new channel through one of the existing fields of the original intake structure. The second field of the existing intake structure will be left as a bypass to improve the discharge in the fish pass to the required value (2 $m^3 \cdot s^{-1}$).

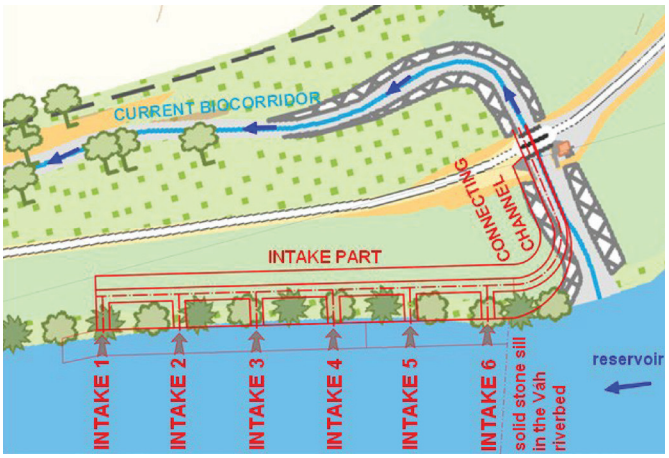


Fig. 3 *Layout of the redesigned intake structure*

The idea is that, after the overflow through the window while it is operating, the water will flow through a short connecting channel into the new fish pass channel, which will be located between the intake wall and a right-hand dike. The new channel of the fish pass (from the intake wall to the original intake structure) will have a zero longitudinal slope (a stream pool will be created).

There were 6 simulation sets according to the approval needed for the intake structure´s capacity. While the discharge in the main river was kept at an average discharge value of 95.6 $m^3 \cdot s^{-1}$, the operational water level at the Žilina water structure differs, depending on each intake window´s position, e.g., H = 352.2, 351.9, 351.6, 351.3, 351.0 and 350.7 m a. s. l.

The crucial criterion for assessing the suitability of the designed intake structure is to achieve the required discharge in the fish pass, cover the fluctuations of the operating levels, and not exceed the flow velocity limit, which was set for the inflow facility at 1.5 $m \cdot s^{-1}$ (this corresponds to a large chamber pool ramp with barriers in the barbel zone). The final design of the intake structure was selected from various proposed designs, which were simulated using a 2D hydrodynamic model. As a primary tool to determine the hydrodynamic conditions at the intake structure, the 2D HEC-RAS software (HEC-RAS Documentation, 2022) was used. The HEC-RAS 2D modelling tool can be used in situations involving detailed 2D channel and floodplain modelling, combined 1D and 2D modeling, simplified dam or levee failure studies, and numerous other tasks.

The 2D Full Momentum computational method, also known as the St. Venant equations for shallow water, was used. Solving the St. Venant equations involves higher computational demands and longer solution times. The advantage of this method is the large number of applicable scenarios, including dynamic flood waves, sudden expansion or contraction of flows, mixed flow regimes, and wave propagation (i.e., waves reflecting off walls and structures). If the flow is incompressible, then the unsteady differential form of the mass conservation (continuity) equation is (Eq. (1) (HEC-RAS Documentation, 2022):

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = q \tag{1}$$

where t is the time; u and v are the velocity components in the x- and y- directions, respectively; and q is a source/sink flux term. In vector form, the continuity equation takes the following form (Eq. (2) (HEC-RAS Documentation, 2022):

$$\frac{\partial h}{\partial t} + \nabla \cdot (hV) = q \tag{2}$$

where $V=(u,v)^T$ is the velocity vector, and ∇ is the gradient operator $\nabla=(\partial/\partial x, \partial/\partial y)^T$.

Integrating over a horizontal region with the normal boundary vector n and using the Gauss Divergence theorem, the integral form of the equation is obtained (Eq. (3) (HEC-RAS Documentation, 2022):

$$\frac{\partial}{\partial t} \iiint_{\Omega} d\Omega + \iint_{S} (V \cdot n) dS = Q \tag{3}$$

where the volumetric region Ω represents a three-dimensional space occupied by the fluid, and n is the unit vector normal to the side boundaries S. It is assumed that Q represents any flow that crosses the bottom surface (infiltration) or the top water surface of Ω (evaporation or rain). In this context, the volume Ω will represent a finite volume cell, and the integrals will be computed using information about the fine underlying topography. Every term of the momentum equation has a clear physical counterpart. From left to right, the terms are unsteady acceleration, convective acceleration, the Coriolis term, the barotropic pressure term, momentum diffusion, bottom friction, and wind forcing (HEC-RAS Documentation, 2022).

When the depth is very shallow, the bottom friction term dominates the equation. As a consequence, dry cells take the limit form $V = 0$. Because the conservation of momentum is directionally invariant, the momentum equation may be in any direction. In HEC-RAS, the momentum is computed as normal to each face (Eq. (4) (HEC-RAS Documentation, 2022):

$$\frac{\partial u_N}{\partial t} + (V \cdot \nabla) u_N - f_c u_T = -g \frac{\partial z_s}{\partial N} + \frac{1}{h} \nabla \cdot (v_t h \nabla u_N) - \frac{\tau_{b,N}}{\rho R} + \frac{\tau_{s,N}}{\rho h} \tag{4}$$

where fc is the Coriolis parameter; g is the gravitational acceleration; z_s is the water surface´s elevation; h is the depth of the water; $\tau_{b,x}$ and $\tau_{b,y}$ are bottom shear stresses in the x- and y- directions; R is the hydraulic radius; and $\tau_{s,x}$ and $\tau_{s,y}$ are surface wind stresses in the x- and y- directions, respectively.

The basic 2D computational methodology assumes that the vertical fluid motion is negligible; the velocity is vertically averaged at the cell center (the depth´s averaged flow); the energy head is computed at the cell center; the Manning's roughness coefficient assigned on the cell´s face uses the roughness value at the cell face´s center, and the Manning's roughness coefficient is constant across each cell face, although each cell face can have its own value (HEC-RAS Documentation, 2022).

The numerical model contains two calculation domains:

- the Váh riverbed together with the Varínka riverbed,
- the fish pass channel.

The domains are connected by an empirical scheme of the inflow structure with the capacity calculated according to the continuous results of the inflow velocities and water levels in both domains at the inflow windows (Bytčanková et al., 2021).

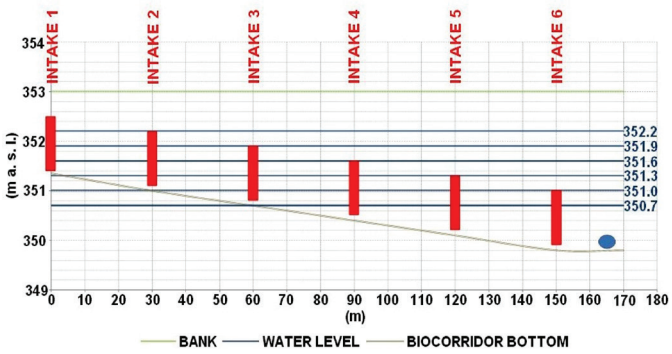


Fig. 4 *Position of the intake windows and the range of operating water levels in the reservoir (order of intake windows from the left, according to Fig. 3)*

3 RESULTS

The new intake structure, with 6 equal intake windows at an axial distance 30 m on the right bank of the reservoir close to the original one (Fig. 4), is designed for a free surface flow in the entire range of the operating levels (assumptions/requirements):

– the fixed top edge of the window is at least 20 cm above the maximum water level for the given window,
– in the range of the operating water levels, the depth of water in the given windows is 70 – 40 cm (in case the width of the opening is too small, the depth of water will be in a range of 60 – 30 cm); the width of the windows will narrow so that at the maximum water level, a discharge of 2 $m^3 \cdot s^{-1}$ will flow through the opening,
– a maximum flow velocity of 1.5 $m \cdot s^{-1}$ is acceptable in the window opening,
– the openings will be equipped with sluice gates without any discharge regulations (this means 2 positions, i.e., open or closed),
– at the end of the intake facility, a water supply structure will be built that will supply minimum discharges in the fish pass so that a minimum discharge of 2 $m^3 \cdot s^{-1}$ is in the fish pass itself; at the same time, it will serve as a backup facility during any failure of the intake structure, so that water will be supplied in the fish pass all the time,
– the regulation range of the possible discharge flow through this structure will be 0 – 2 $m^3 \cdot s^{-1}$.

After a series of calculations, the dimensions of each opening window were designed to be 1.1 m x 1.8 m (height x width). With these dimensions, the following requirements will be met:

– the fixed top edge of a window will be 30 cm above the maximum water level for that window,
– in the range of operating water levels, the depth of the water in the given window will be 80 – 50 cm,
– discharges through the window will be (Tab. 1):
  • at the target water level (at the same time as the maximum water level for the window), Q = 2.56 $m^3 \cdot s^{-1}$ (the difference in the water levels in the reservoir and the fish pass will be 0.37 m),
  • at the middle water level (15 cm less than the target water level), Q = 1.65 $m^3 \cdot s^{-1}$ (the difference in the water levels in the reservoir and the fish pass will be 0.33 m),
  • at the minimum water level (30 cm less than the target water level and the same as the next lower target water level), Q = 0.94 $m^3 \cdot s^{-1}$ (the difference in the water levels in the reservoir and the fish pass will be 0.29 m).

The simulation results show that the intake structure with an uncontrolled flow through the intake windows cannot provide a constant discharge to the fish pass due to the changes in the water level in the main reservoir. When the discharge drops below the required value of 2 $m^3 \cdot s^{-1}$, the water supply structure (built at the end of the intake wall) must supplement the missing discharge. Another way of doing this is to control the flow at the intake windows with the sluice gates of the higher-placed intake window. Based on the results of the numerical model and published hydraulic research on the issue of the distribution of vertical velocity (Velísková et al., 2018; Kašpar et al., 2021; Bytčanková et al., 2021), the course of vertical velocities in the intake opening is stated in Fig. 5 and Tab. 1.

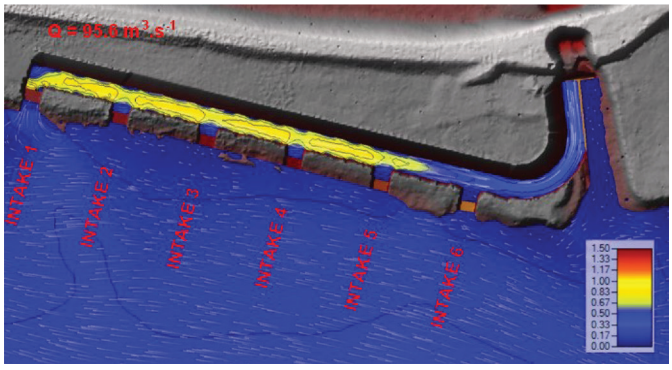


Fig. 5 *Simulated velocity field in the area of the intake structure at an average discharge of 95.6 $m^3 \cdot s^{-1}$ in the Váh River and an operational water level of 350.7 m a. s. l. at the Žilina water structure (order of intake windows from the left, according to Fig. 3)*

Tab. 1 *Final results from the hydraulic research for a single window*

water level in the intake window	discharge through the window	difference in the water level at the window	depth in the window	average velocity	velocity on the water surface	velocity at the bottom of the window
	($m^3 \cdot s^{-1}$)	(m)	(m)	($m \cdot s^{-1}$)	($m \cdot s^{-1}$)	($m \cdot s^{-1}$)
maximum	2.56	0.37	0.80	1.8	2.0	1.2
middle	1.65	0.33	0.65	1.4	1.6	1.0
minimum	0.94	0.29	0.50	1.0	1.1	0.7

4 CONCLUSIONS

There is a complex spatial flow in and around intake structures. Hydraulic calculations are performed under certain conditions. The velocities and discharges are also conditioned by the shape and width of the opening edge and other construction modifications on the intake structure, the connecting channel, and the fish pass bed. Based on the recommendations of an ecologist consultant, it would be necessary to further reduce velocities on the intake bed and immediately behind it. This can be achieved with several adjustments. One option is to increase the number of windows, which also means increasing the number of target water levels. This would reduce the difference in the water level between the target levels for each intake window. Another option, which would be also recommended, is to increase the roughness on the river bed bottom locally by individual/single stones (by keeping the number of intake windows to 6). It is assumed that such an adjustment would also reduce the discharge through the structure, which could be partially compensated for by increasing the width of the window. However, this would require more detailed research using 3D mathematical or physical models.

The intake structure is one of the key structures in the design of any type of fish pass. During a time of climate change, when the water levels in streams change, an intake structure with flow controls is the most suitable design with which to provide the operating conditions of fish passes. In the past, commonly used intake windows, which were placed on several levels covering the operational range of the water levels during the operation of water structures, have been a relatively simple solution. Verification of the complex 3D flow in and around these intake structures is the subject of verification on physical models, where it is possible to measure the discharges, depths, and velocities for different operating conditions, which can be achieved by the design of this structure to ensure its functionality after its construction.

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