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STEPGRAD
СТЕПГРАД

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ECOLOGICAL AND HYDROTECHNICAL ASPECTS OF FISH PASSAGE DESIGN – A CASE STUDY OF THE DJERDAP 2 HYDROPOWER PLANT

Abstract:

Fish passages represent a key engineering and ecological measure for restoring the longitudinal connectivity of watercourses disrupted by hydraulic structures. This paper presents the conceptual design of a nature-like fish passage at the Djerdap 2 hydropower plant on the Danube River. The study includes route definition, hydraulic sizing under complex site constraints, and assessment of ecological compatibility using literature-based criteria for relevant migratory fish species. The adopted concept was developed with reference to the fish passage at Freudenau in Vienna. The results indicate hydraulically feasible and ecologically acceptable internal flow conditions, while additional modelling of the entrance zone is recommended for final design verification.

Keywords: fish passage; Danube River; ecological continuity; hydraulic calculation; close-to-nature fishway

ЕКОЛОШКИ И ХИДРОТЕХНИЧКИ АСПЕКТИ ПРОЈЕКТОВАЊА РИБЉЕ СТАЗЕ – СТУДИЈА СЛУЧАЈА ХЕ ЂЕРДАП 2

Сажетак:

Рибље стазе представљају важну инжењерску и еколошку меру за обнављање лонгитудиналне повезаности водотока нарушене изградњом хидротехничких објеката. У раду је приказано концептуално решење природи блиске рибље стазе на хидроелектрани Ђердап 2 на реци Дунав. Истраживање обухвата дефинисање трасе, хидраулично димензионисање у сложеним локацијским условима и оцену еколошке компатибилности на основу критеријума из литературе за релевантне миграторне врсте риба. Усвојени концепт развијен је по угледу на рибљу стазу у Фројденау у Бечу. Резултати указују на хидраулички изводљиве и еколошки прихватљиве унутрашње услове течења, док се за коначну верификацију решења препоручује додатно моделирање улазне зоне.

Кључне ријечи: рибља стаза; Дунав; еколошки континуитет; хидраулички прорачун; close-to-nature fishway

1. INTRODUCTION

Fragmentation of watercourses caused by the construction of dams, weirs, and other hydraulic structures represents one of the dominant pressures on river ecosystems at the global scale [1], [2]. Disruption of longitudinal connectivity directly affects fish migration routes, genetic exchange, and habitat availability, leading in the long term to biodiversity loss and degradation of ecological functions of watercourses [3], [4].

The contemporary concept of water resources management, defined by the EU Water Framework Directive (WFD), is based on the preservation or achievement of good ecological status of surface waters, with river continuity recognized as a key hydromorphological element [1]. In this context, fish passages represent a standard engineering solution for mitigating the negative impacts of hydraulic structures on fish migration and the functioning of aquatic ecosystems [3], [4], [5].

Designing fish passages requires an interdisciplinary approach that integrates open-channel hydraulics, fish ecology, and principles of biological permeability. Key design parameters include flow velocity, water depth, energy dissipation, pool geometry, and flow continuity [3], [6], [7]. Although fish passages have been implemented in practice for decades, a significant proportion of constructed facilities fail to achieve full functionality under real operating conditions, most often due to inadequate hydraulic dimensioning, insufficient consideration of the biological characteristics of local fish populations, and poor adaptation to variable flow and water-level regimes [4], [8].

In the Republic of Serbia, many existing hydraulic structures were built during periods when ecological requirements were not systematically incorporated into engineering practice, which makes their subsequent alignment with contemporary standards an important task [2]. The aim of this paper is to present a conceptual design solution for a nature-like fish passage on the Danube River at HPP Djerdap 2 and to assess the ecological compatibility of the adopted hydraulic parameters with the migration requirements of relevant fish species.

The study focuses on a large regulated river system characterized by a substantial head difference, variable hydrological conditions, and strict operational constraints related to hydropower operation. In this context, the contribution of the paper lies in demonstrating the feasibility of adapting a close-to-nature fishway concept to the Djerdap 2 site, using the fish passage at the Freudenau Hydropower Plant in Vienna as a reference example of good practice for large-river conditions [9].

Rather than presenting a fully iterative ecohydraulic optimization, the methodology combines hydraulic design of the fish passage with a subsequent ecological compatibility assessment based on literature-derived criteria applicable to large Danube river systems.

2. METHODOLOGY FOR CALCULATION AND EVALUATION

The methodology applied in this study combines hydraulic design of the fish passage with an ecological compatibility assessment of the obtained design parameters. The objective was to define a hydraulically feasible concept for the Djerdap 2 site and then evaluate whether the resulting flow conditions are compatible with literature-based migration criteria applicable to relevant migratory fish groups in large Danube river systems. The approach is adapted to large-river conditions and relies on a combination of analytical calculations, available design documentation, literature-derived ecological criteria, and comparative consideration of a reference fish passage example at the Freudenau Hydropower Plant in Vienna. The methodological procedure includes the following steps:

- collection and systematization of input data on the Danube water level and discharge regime (low, mean, and high flows), including ecological minimum flow and extreme hydraulic conditions;
- determination of the available head difference between upstream and downstream water levels and its distribution along cascades and pools of the fish passage;
- selection of the fish passage type (a close-to-nature bypass with ramps along the banks and bottom) in accordance with the hydraulic and ecological requirements of the site;
- hydraulic dimensioning of the cross section using the Chezy–Manning equation for open-channel flow, with the roughness coefficient selected to represent a natural, stone-lined channel;
- calculation of characteristic flow velocities, water depths, and discharges through the fish passage under different operating regimes;
- assessment of the head drop per cascade and specific energy dissipation in pools as key criteria of hydraulic acceptability;

- dimensioning of the flow-control gate for regulating discharge through the fish passage under minimum and increased inflow conditions;
- ecological compatibility assessment of the obtained hydraulic parameters through comparison with literature-based migration criteria applicable to large Danube river systems.

The ecological assessment was carried out indirectly by examining the compliance of the designed hydraulic parameters (flow velocity, water depth, head drop per cascade, and energy dissipation) with recommended threshold values from relevant literature for close-to-nature fish passages. Particular attention was given to resting zones in the form of pools between cascades, hydraulic continuity over a wide range of water levels, and the general suitability of the internal flow conditions for medium-sized migratory fish species relevant to the lower Danube.

The present study was not based on species-specific biological design criteria, since detailed site-specific data on target fish species and their swimming performance were not available within the scope of the study. Therefore, the ecological assessment was conducted using literature-based hydraulic criteria commonly applied to close-to-nature fish passages, with reference to migratory, rheophilic, and potamodromous fish groups relevant to large Danube river systems. Consequently, the proposed solution should be interpreted as a concept-level hydraulic design with ecological compatibility assessment, while the identification of target species and biological validation of passage efficiency should be addressed in a subsequent project phase.

Site-specific ichthyological data for the exact fish-pass location were not available within the scope of the present study. As an additional methodological component, a qualitative comparative analysis was conducted using examples of good practice, particularly the fish passage at the Freudenau Hydropower Plant in Vienna, which served as a reference example for assessing the plausibility of the adopted design parameters under large-river operating conditions. Based on the performed calculations and comparisons, the proposed solution was evaluated from both hydraulic and ecological perspectives at the concept-design level.

Due to the conceptual design stage and the availability of detailed hydraulic documentation for the HPP Djerdap 2 system, analytical dimensioning based on the Chezy–Manning equation was considered sufficient for the present study. Numerical hydraulic modelling (e.g. CFD simulations) is recommended as a subsequent step in the detailed design phase in order to further refine velocity distribution, turbulence characteristics, and entrance-zone flow conditions.

3. ECOLOGICAL SIGNIFICANCE OF FISH PASSAGES

Fish passages have ecological significance only if their hydraulic and morphological characteristics enable actual fish movement under variable operating conditions [1], [3], [4]. In large regulated rivers, this requires not only restoring longitudinal continuity in principle, but also ensuring that flow velocities, water depths, head drops, and resting opportunities remain compatible with the migration requirements of relevant migratory fish groups in large Danube river systems [4], [6], [7]. In the case of the Danube River at HPP Djerdap 2, the ecological importance of the proposed fish passage lies in its potential to mitigate the barrier effect of the hydropower system and to improve migration conditions for native rheophilic and potamodromous fish species relevant to the lower Danube [1], [2], [3].

4. CASE STUDY – HYDROPOWER PLANT DJERDAP 2 ON THE DANUBE RIVER

The Danube River is one of the most important European watercourses, serving simultaneously as an international navigation route and an ecological corridor. Intensive regulation and the construction of hydraulic structures have enabled the development of hydropower generation, navigation, and flood protection, but have also led to fragmentation of the river ecosystem and disruption of migratory connectivity [1], [2], [3].

The fish passage considered in this study is designed as a close-to-nature solution, consisting of a bypass channel with ramps along the banks and bed, ensuring that the permanent ecological minimum flow is conveyed downstream through the fish passage. The adopted concept was developed with reference to the fish passage at the Freudenau Hydropower Plant in Vienna, while being adapted to the specific hydraulic, morphological, and operational constraints of the Djerdap 2 site. The elevation of the intake to the supply channel at the crest of the spillway weir must be higher than the elevation of the designed outlet for the ecological minimum flow, in order to ensure continuous feeding of the fish passage.

4.1. BASIC DATA AND WATER LEVEL REGIME

Table 1. Basic data and water level regime

Quantity	Symbol	Value
Crest elevation	H_c	43.50 m
Maximum upstream water level	$H_{u,max}$	41.00 m
Minimum upstream water level	$H_{u,min}$	39.70 m
Minimum downstream water level	$H_{d,min}$	29.34 m
Total head difference (at H_u,min)	ΔH_{total}	10.36 m
Total head difference (at H_u,max)	$\Delta H_{total,max}$	11.66 m
Average annual inflow (2012)	Q_{avg}	4 406 m³/s
Maximum mean daily inflow	$Q_{d,max}$	7 100 m³/s
Maximum annual inflow	$Q_{a,max}$	7 383 m³/s
Minimum annual inflow	$Q_{a,min}$	2 169 m³/s

Note: The inflow data were taken from the design documentation and dispatch services of the HPP Djerdap 1 and Djerdap 2 hydropower plants.

The presented water-level regime indicates that the fish passage must operate under a substantial and variable total head difference, which strongly influences the required length of the alignment, internal energy dissipation, and the design of the entrance and control structures.

4.2. ALIGNMENT AND FUNCTIONAL ZONES OF THE FISH PASSAGE

The alignment of the fish passage is planned along the right bank of the Danube River (Serbian side). The total length of the alignment is approximately 1 450 m. The entrance to the fish passage (water outlet) is located about 500 m downstream of the dam, while the exit from the fish passage (water inlet) is approximately 350 m upstream of the dam.

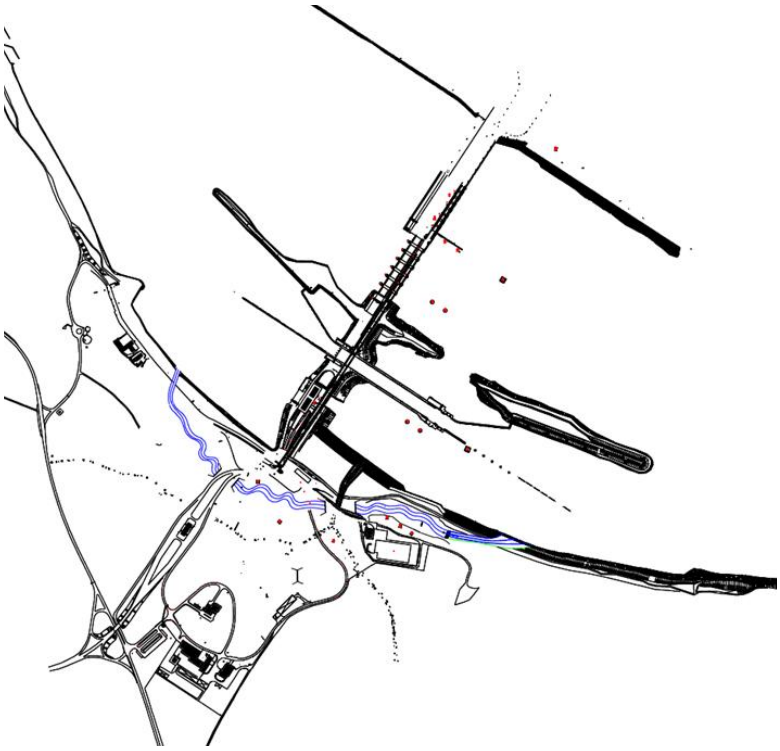

Figure 1. Fish Passage Alignment (Site Plan) (drawing by author in AutoCAD).

The entrance zone is designed in the form of a delta with three branches. Two branches are permanently in operation, while the third is activated during water levels exceeding mean flow conditions. The length of the delta is approximately 200 m, with each branch having a length of about 200 m and a width of approximately 6 m.

The adopted delta-shaped entrance was conceived as a preliminary solution intended to improve local attraction conditions and flow guidance toward the fish-pass opening; however, its hydraulic effectiveness under real river conditions should be verified in a subsequent design phase by detailed two-dimensional or three-dimensional hydraulic modelling.

The main section of the fish passage consists of a bypass channel approximately 1 000 m long, combining straight and meandering reaches in order to reduce flow velocities and provide diverse hydraulic conditions. The final section comprises bank and bed ramps approximately 250 m long, incorporating pools/resting areas.

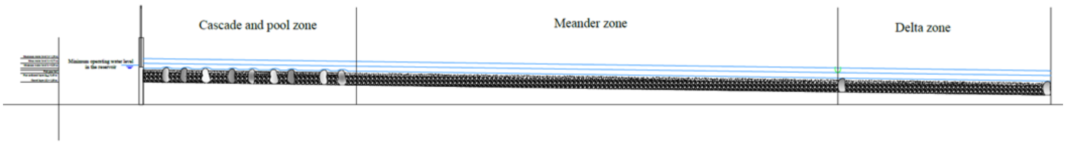

Figure 2. Longitudinal Profile of the Fish Passage with Delta, Meander, and Cascade Zones (drawing by author).

4.3. HYDRAULIC CONDITIONS OF THE FISH PASSAGE ON THE DANUBE

The hydraulic operating conditions of the fish passage are defined by the water level and discharge regime of the Danube, as well as by the relationship between upstream and downstream water levels at the project location. The fish passage overcomes a total head difference ranging from approximately 10.36 m (at minimum upstream water level) to 11.66 m (at maximum upstream water level).

In addition to hydraulic variability, the Danube River at the project location is characterized by significant sediment transport processes, particularly during high-flow events. Sediment deposition and local bed adjustments may influence flow distribution and cross-sectional geometry of the fish passage over time. Therefore, the adopted design includes geometrical flexibility and maintenance accessibility to mitigate potential long-term morphodynamic impacts.

Flow velocity in the river reach near the water intake varies due to the local bed slope (approximately 2.86%), and depending on the water level, ranges from about 0.40 m/s (low-flow conditions) to approximately 2.00 m/s (100-year flood conditions). For this reason, a meandering/traversing alignment with alternating pools and rapids was adopted in the design in order to reduce flow velocities within the fish passage to values acceptable for fish migration.

Based on the reference example of the fish passage at the Freudenau Hydropower Plant in Vienna and the site-specific conditions at Djerdap 2, a concept-level discharge range was adopted for the fish passage. The selected discharge through the fish passage is significantly lower than the main river discharge and is defined as part of the ecological minimum flow, with regulation ensured by a control gate. The adopted operating range was selected to ensure hydraulic continuity, minimum water depth, and acceptable internal flow velocities within the fish passage, while remaining compatible with the available head difference and the geometric constraints of the site.The adopted discharge range of 1.8–3.6 m^3/s should be understood as a concept-level operating envelope for the fish passage. The lower bound corresponds to the minimum discharge required to ensure continuous flow and sufficient water depth in the shallowest sections of the bypass and ramp zones. The upper bound represents an increased operating discharge intended to improve passage hydraulics and hydraulic attractiveness under more favourable hydrological conditions, while maintaining acceptable head drops and energy dissipation within the pools.

The design discharges through the fish passage are significantly lower than the main river discharge and are defined as part of the ecological (biological) minimum flow, with regulation ensured by a control gate.

The main design criteria are as follows:

- channel bed slope: 1:10 to 1:20 (for a close-to-nature type),
- minimum channel bottom width: $b \geq 0.80$ m,
- minimum water depth: $h \geq 0.25$ m (in the project, $h_{\min} \approx 0.20$ mis permitted in certain zones),
- recommended mean velocity: $v = 0.40 - 0.60\, m/s$; maximum velocity $\text{v} \leq 1.60 - 2.00\, m/s$,
- alignment: straight or meandering, with alternating pools and rapids,
- bank protection: large rock, sills, and bioengineering stabilization measures,

- minimum discharge through the fish passage: $q \geq 0.10\ \mathrm{m^3/s}$ (in the project, a significantly higher value was adopted).

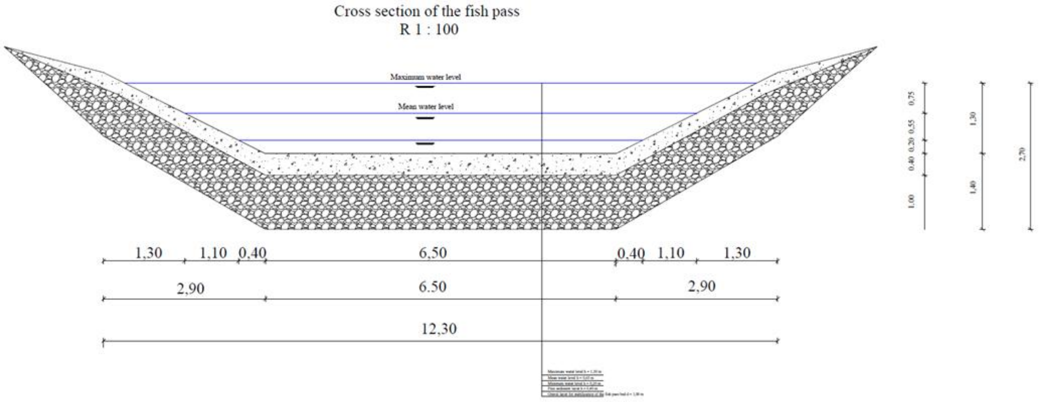

Figure 3. Cross-section of the fish passage (drawing by author).

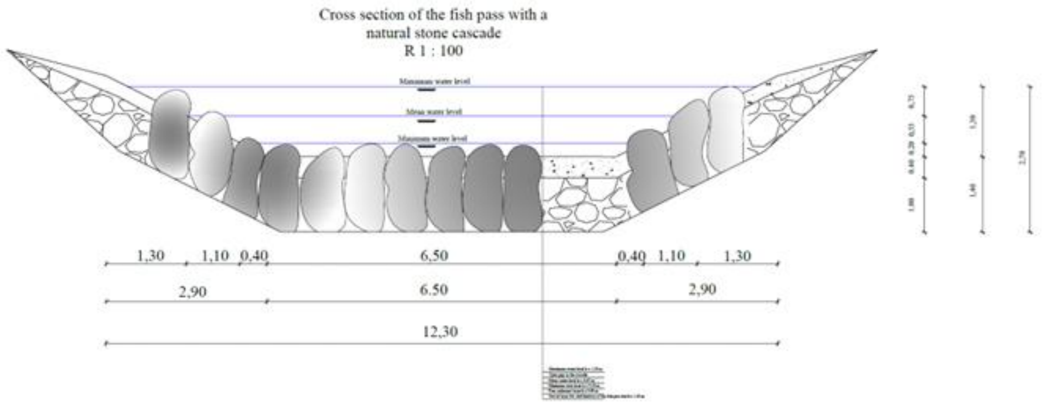

Figure 4. Cross-section of the fish passage with a natural stone cascade (drawing by author).

5. HYDRAULIC DESIGN OF THE FISH PASSAGE

The hydraulic design of the fish passage aims to ensure flow conditions compatible with the migration requirements of target fish species, while providing stable operation over a wide range of water levels and safe energy dissipation.

The design is based on the available head difference between upstream and downstream water levels, the geometry of the fishway (width, depth, cross-sectional shape), the number of cascades/pools, and the selected discharge through the fish passage.

In the present study, hydraulic design was evaluated in relation to literature-based ecological criteria for medium-sized migratory fish species relevant to the lower Danube, rather than through a fully species-specific biological optimization [3], [4], [6].

Within the HPP Djerdap 2 project, the minimum discharge through the fish passage was adopted as $Q_{min} = 1.36$ m3/s (1800 l/s), while during medium-flow conditions an increase up to $Q_{max} = 3.6\ m^3/s$ is foreseen, with the possibility of seasonal variations. The adopted discharge range should be understood as a concept-level operating envelope. The lower bound corresponds to the minimum discharge required to ensure hydraulic continuity and sufficient water depth in the shallowest sections of the fish passage, while the upper bound represents an increased operating discharge intended to improve passage hydraulics and local hydraulic attractiveness under more favourable hydrological conditions, while maintaining acceptable head drops and energy dissipation within the pools [3], [4], [6].

The adopted range was defined with reference to the Freudenau example and adjusted to the specific head difference, geometry, and operational constraints of the Djerdap 2 site.

5.1. CROSS-SECTIONAL DIMENSIONING

For dimensioning, a trapezoidal cross-section was adopted, as it provides favorable hydraulic conditions and a close-to-nature appearance.
The discharge is determined using the Chezy–Manning equation:

$$Q = \left(A \cdot R^{2/3} \cdot I^{1/2}\right)/n \tag{1}$$

where:
- A – the flow cross-sectional area (m^2),
- $R = A/\chi$ – hydraulic radius (m),
- χ – wetted perimeter (m),
- I – longitudinal bed slope (%),
- n – Manning roughness coefficient $\left(s \cdot m^{-1/3}\right)$.

In the study, the following values were adopted: $n = 0.047 s \cdot m^{-1/3}$ and bed slope $I = 0.9$).
For a discharge of $Q = 1.8 m^3/s$ and the minimum operating depth, the required cross-sectional flow area is obtained as $A \approx 1.50\, m^2$.
The adopted Manning roughness coefficient of n=0.047 was selected to represent a roughened near-natural channel with coarse stone elements, bed irregularities, variable microtopography, and local vegetation influence.
Such hydraulic resistance is consistent with the intended close-to-nature character of the bypass and contributes to reduced mean flow velocities and more diverse hydraulic habitats [10], [11].

Table 2. Hydraulic Design Parameters for Cross-Sectional Dimensioning

Quantity	Symbol	Value
Manning roughness coefficient	n	0.047
Channel bed slope	I	0.009 (0.9%)
Minimum discharge through the fish pass	Q_{min}	1.8 m^3/s
Bottom width	b	≈6.50 m
Water surface width (at h_{min})	B	≈6.90 m
Minimum water depth	h_{min}	0.25 m
Maximum water depth	h_{max}	1.30 m

5.2. HEAD DIFFERENCES, FLOW VELOCITIES, AND ENERGY DISSIPATION PER CASCADE

The ramp section along the banks and the bed is designed with 9 pools. The maximum head difference per cascade under low-water conditions is approximately $\Delta H \approx 0.11$ m, while in the entrance zone 3–4 smaller cascades with a height of up to 0.20 m (recommended ≈ 0.16 m) are provided in order to improve local hydraulic guidance toward the entrance and to create a recognizable flow pattern.
However, the effectiveness of this solution in terms of attraction flow should be verified in a subsequent design phase by detailed hydraulic modelling of the entrance zone [3], [4], [6].
To assess the hydraulic loading, the specific energy dissipation (specific power) within each pool is used:

$$E = \rho \cdot g \cdot Q \cdot \Delta H \,/\, V \tag{2}$$

where:
- V – pool volume (m^3).

Table 3. Calculated values of specific energy dissipation per pool for characteristic fish pass discharges

Regime	Q (m^3/s)	ΔH per pool (m)	Pool volume (m^3)	E (W/m^3)
Minimum discharge	1.8	0.11	36	54
Medium flow (maximum case)	3.6	0.11	36	108

For a representative pool: $V \approx 20m\ \cdot 3\ m \cdot 0.60\ m = 36\ m^3$, the following values are obtained: $E \approx 54W/m^3$ for Q_{min} and $E \approx 108W/m^3$ for Q_{max}.
These values remain below the commonly accepted threshold for ecologically acceptable hydraulic conditions (typically $150\ W/m^3$, with $200\ W/m^3$ considered an upper threshold) [3], [6].
Table 4 summarizes the compliance of the designed hydraulic parameters with commonly recommended ecological thresholds for close-to-nature fish passages. Recommended values are derived from commonly cited fish passage design guidelines [3], [4], [6].

Table 4. Comparison of recommended ecological criteria and designed hydraulic parameters

Parameter	Commonly Recommended Range (Literature-Based)	Designed Value
Velocity	0.4–2.0 m/s	0.6 m/s
ΔH per cascade	≤ 0.20 m	0.11 m
Energy dissipation	≤ 150 W/m^3	54–108 W/m^3
Minimum water depth	≥ 0.25 m	0.25 m
Resting zones / pools	Required	Provided
Attraction flow at entrance	Should be hydraulically effective	Requires further verification

5.3. DISCHARGE CONTROL GATE CALCULATION

At the outlet of the fish pass (water intake zone), a control gate is designed to regulate the discharge through the fish pass and to allow complete closure in case of maintenance or emergency. The design condition requires that the minimum discharge through the fish pass be maintained at $Q_{min} = 1.8\ m^3/s$, for a weir head of $H = 0.25\ m$. The required crest width is determined using the standard weir discharge equation:

$$Q = m \cdot b \cdot \sqrt{(2g)} \cdot H^{3/2} \tag{3}$$

where:

- m – contraction coefficient (adopted m = 1),
- b – crest width (m),
- g – gravitational acceleration (9.81 m/s^2),
- H – head over the crest (m).

Rearranging the equation for the crest width gives:

$$b = Q/\left(m \cdot \sqrt{(2g)} \cdot H^{3/2}\right) \approx\ 3.27\ m.$$

A steel gate with dimensions $3.27 \times 1.60 \times 0.10$m is proposed, with automatic actuation and backup manual control to ensure operational reliability under different operating conditions.

Table 5. Hydraulic Design Parameters and Calculated Dimensions of the Fish Pass Control Gate

Parameter	Symbol	Value
Minimum discharge	Q_{min}	$1.8 m^3/s$
Contraction coefficient	m	1.0
Weir head	H	$0.25\ m$
Weir crest width	b	$3.27\ m$
Proposed steel gate dimensions	–	3.27 · 1.60 · 0.10 m

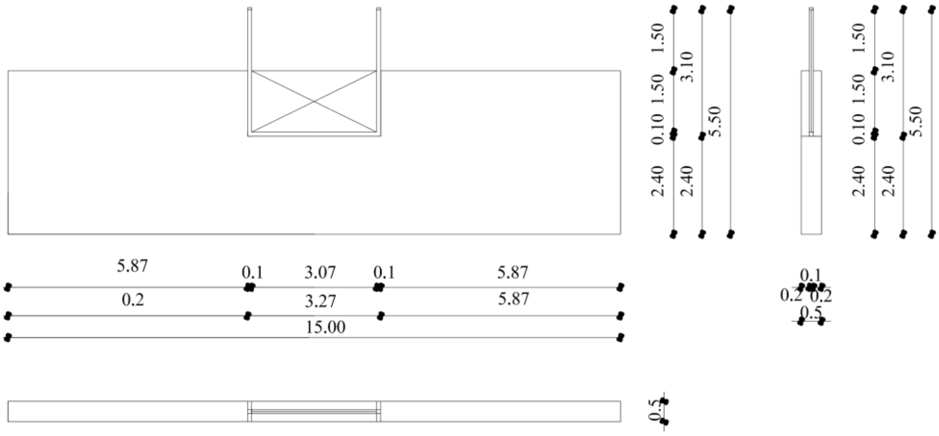

Figure 5. Detail of the concrete wall with a flow-regulating gate (drawing by author).

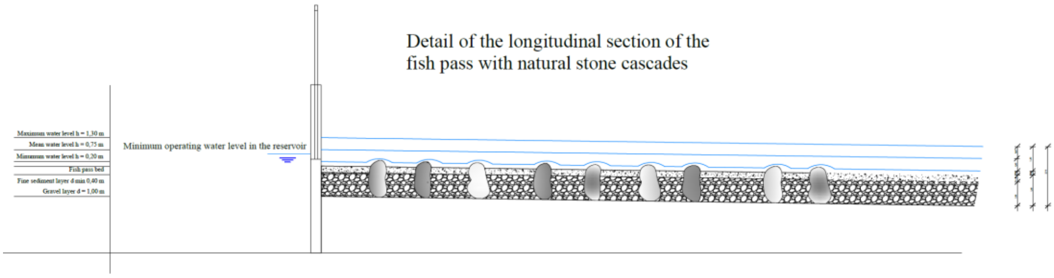

Figure 6. Detail of the longitudinal section with natural stone cascades(drawing by author).

6. TECHNICAL SOLUTION

The technical solution of the fish pass is based on the principle of restoring migration continuity for ichthyofauna while adapting the structure to the hydraulic and morphological conditions of the Danube riverbank zone. The solution combines a close-to-nature bypass channel and a section of ramps along the banks and channel bed, enabling gradual overcoming of the total head difference through controlled flow velocities and sufficient resting zones.

The alignment of the fish pass was designed to avoid conflicts with the existing infrastructure of HPP Djerdap 2.

Potential road crossings are resolved by small bridges (culverts are excluded to preserve both the natural appearance and hydraulic conveyance capacity). The hydropower plant installations are located at depths greater than the maximum depth of the fish pass; however, protective measures must be implemented during construction to prevent damage.

Table 6. Main Technical Parameters

Parameter	Value
Total alignment length	≈ 1 450 m
Delta (inlet zone) length	≈ 200 m (3 branches, width ≈ 6 m each)
Bypass length	≈ 1 000 m
Ramp section length	≈ 250 m
Number of pools (ramp section)	≈ 9
Max. head drop per cascade (low flow)	≈ 0.11 m
Minimum discharge through fish pass	1.8 m^3/s
Maximum (design) discharge	3.6 m^3/s
Construction material	Reinforced concrete + natural stone
Flow regulation	Gate (automatic + manual control)

The fish pass bed is designed as a gravel-sand layer approximately 1.0 m thick, with an additional layer of natural deposits (≈0.40 m), ensuring structural stability and maintaining the natural character of the channel. The banks are protected with large stones and/or sills, combined with bio-engineering measures (planting of native trees and vegetation, root system stabilization and reed reinforcement) to prevent erosion and enhance ecological conditions.

Cascades and ramps are constructed from natural stone (recommended block dimensions 30–50 cm), asymmetrically arranged to create flow diversity and refuge zones.

The stones are anchored into the foundation layer to ensure stability under variable water levels. The height of an individual ramp must not exceed 0.20 m above the channel bed, and each ramp includes an open slot ("empty row") to facilitate fish migration.

7. DICUSSION

The presented results indicate that the proposed nature-like fish-passage concept is hydraulically feasible at the Djerdap 2 site and that its main internal hydraulic parameters are broadly compatible with literature-based ecological criteria for medium- and large-bodied rheophilic fish species. In the case of the Danube River at HPP Djerdap 2, particular attention was given to the entrance concept, functionality over a wide range of water levels, controlled energy dissipation within pools, and compatibility with the operational regime of the hydropower system [3], [4], [6].

The calculated hydraulic parameters indicate that flow velocities and head drops per cascade remain within ranges generally considered acceptable for medium- and large-bodied rheophilic fish species. The specific energy dissipation values (54–108 W/m^3) remain below commonly cited ecological thresholds, suggesting that excessive turbulence and fish fatigue are unlikely under design conditions.

However, several practical and operational limitations should be considered. In large rivers with significant sediment transport, deposition processes may alter local bed geometry and affect hydraulic performance over time. In addition, extreme hydrological events, potentially intensified under climate change scenarios, may influence the hydraulic regime in the entrance and outlet zones. Therefore, long-term functionality depends not only on initial hydraulic dimensioning but also on adaptive management and regular maintenance.

Close-to-nature fish passages are particularly sensitive to vegetation growth and sediment accumulation, especially in low-flow periods. Without systematic inspection and sediment removal, hydraulic conditions may deviate from design assumptions, potentially reducing ecological effectiveness.

For these reasons, hydraulic monitoring (water levels, discharge through the fish pass, velocity distribution) combined with biological monitoring (fish counters, telemetry studies) is recommended in order to verify actual passage efficiency and to enable future optimization of operational parameters.

At the current stage, the presented evaluation is based on hydraulic criteria and established ecological threshold values from relevant literature. Comprehensive biological monitoring (including fish counting systems, telemetry tracking, and seasonal migration analysis) is foreseen as a subsequent phase in order to validate passage efficiency under real operating conditions and to quantify species-specific performance indicators.

8. CONCLUSION

This study presents a concept-level hydraulic design of a nature-like fish pass at HPP Djerdap 2 on the Danube River, together with an ecological compatibility assessment of the adopted hydraulic parameters. The results indicate that a total head difference of approximately 10.36–11.66 m can be overcome by a cascade system with controlled head drops of approximately 0.11 m per segment, while maintaining a minimum discharge of 1.8 m^3/s. Cross-sectional dimensioning based on the Chezy–Manning equation ($n=0.047$, $I=0.9\%$) indicates hydraulically stable operation within the defined discharge range. The calculated specific energy dissipation values remain within commonly recommended ecological limits, reducing the risk of excessive turbulence and fish fatigue.

The design of the discharge control gate provides operational flexibility and reliable regulation of ecological flow under varying hydrological conditions, ensuring compatibility between ecological requirements and hydropower operation.

The presented case study indicates that adaptation of a close-to-nature fish-pass concept to a large regulated river system is technically feasible without compromising the primary hydropower function, provided that hydraulic design is complemented by ecological compatibility assessment and subsequent biological verification under real operating conditions. Future research should focus on long-term hydraulic and biological monitoring, including telemetry-based fish tracking and adaptive operational strategies, in order to verify passage efficiency under real operating conditions and to further refine design methodologies for large-river fish passes

SUSTAINABLE DEVELOPMENT GOALS: Sustainable Cities and Communities

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