



DEVELOPMENT OF THE COMBINED FISH PASS OF FRATEL'S DAM USING NUMERICAL AND PHYSICAL MODELLING

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ABSTRACT

In 2025, EDP, Portugal's leading energy production and distribution company, will carry out intervention at the Fratel Hydroelectric Scheme on the Tagus River, to improve the power production efficiency and to provide migratory fish access to upstream habitats. The tailrace channel will be reprofiled, and a new fish pass system was designed, which is the focus of this study. The project aims to enable fish migration past the powerhouse afterbay sill, even during low water levels, and reach the future fish lock.

The fish pass system comprises three key elements: a 230-metre-long fish-dedicated channel, excavated along the tailrace, a four-pool fishway, and a bypass channel with irregular baffle walls.

A comprehensive study conducted at the National Civil Engineering Laboratory of Portugal (LNEC) employed computational fluid dynamics (CFD) and physical modelling to optimise the system proposed by EDP. Velocity fields and flow depths across varying operational scenarios were evaluated. A multidisciplinary team, comprising experts in hydraulic engineering, computational and physical modelling, and ecological science from LNEC, EDP, and MARE/University of Évora, worked in close collaboration, recommending design optimizations.

The large domain dimensions would imply an unfeasibly large physical model. Similarly, a single CFD model to accurately reproduce all geometries would be computationally prohibitive due to the range of time and length scales involved. Hence, the combination of CFD and physical modelling was essential for detailed testing of several design iterations, minimising physical trials, and significantly reducing costs.

CFD enabled the modelling of the whole domain. The fish migration conditions between the tailrace confluence with the Tagus River and the afterbay sill were analysed in detail using a volume-of-fluid model, whereas the pool fishway was modelled indirectly. Concurrently, a 1:10 scale physical model focused on the afterbay, the pool fishway, and the bypass channel. This facilitated detailed insights regarding fish migration past the afterbay sill and the fish lock discharge attraction potential, further refining the design.

The project's success was driven by the integrated CFD and physical modelling approach and the interdisciplinary effort, demonstrating the critical role of collaboration in advancing eco-friendly hydraulic infrastructures.

Keywords: Dam, Eco-hydraulic, Fish pass system, Computational modelling, Physical modelling.

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1. INTRODUCTION

1.1. Background and Context

Hydroelectric dams have a critical role in the production and storage of renewable energy, contributing to the reduction of greenhouse gas emissions [1]. However, these infrastructures pose negative ecological impacts on riverine ecosystems, including habitat fragmentation due to barriers to fish migration, altered flow regimes and dissolved gases and nutrients concentrations [2]. Moreover, the artificialization of river stretches in the tailrace channels, and hydropeaking operations — characterized by sudden discharge variations to meet energy demands — alter river hydromorphology and disrupt fish behaviour [3,4,5].

Effective fish pass systems are essential to restore connectivity and promote biodiversity conservation, mitigating the ecological disruptions. However, the design and operation of these systems often face significant engineering challenges due to site-specific hydraulic and biological constraints. River systems require innovative approaches to address the unique hydrological and ecological dynamics posed by these constraints. Emerging research highlights the complexities of fish migration, including alternative migration patterns influenced by environmental cues. Moreover, invasive species, which compete for resources and disrupt native habitats, further complicate ecological restoration efforts, emphasizing the value of holistic approaches to ecological restoration [6].

Addressing these compounded impacts demands multidisciplinary and collaborative efforts to develop site-specific methodologies, that combine advanced technological and ecological knowledge [7]. After monitoring and evaluating, each case-study may also provide valuable insights for similar ecosystems worldwide.

1.2. Relevance of the Study

The Fratel Hydroelectric Scheme on the Tagus River is paradigmatic. Operational since 1974, the dam has since been part of the Portuguese hydropower system [8]. However, it disrupted ecological connectivity in this important river system, impacting migratory fish species reliant on upstream habitats for critical life stages [5]. In 2025, EDP, the main energy production and distribution company in Portugal, will undertake an intervention, involving the reprofiling of the tailrace channel and the development of a new fish pass system, to improve the power production efficiency and, simultaneously, to provide better conditions for migratory fish to access upstream habitat.

This intervention aligns with global strategies to balance hydropower development with ecological preservation. It will be a significant step to enhance connectivity to upstream habitats, hence, reconnecting fragmented ecosystems along the Tagus River [6]. The fish pass

system is designed to enable migratory fish to swim past the powerhouse afterbay sill, even during low water levels, reaching the entrance of a future fish lock.

The fish pass system comprises three elements. A 230-metre-long channel, excavated along the tailrace reprofiled channel, enables migration during low water levels, and provides resting areas. A four-pool fishway and a bypass channel with irregular baffle walls allow fish movement past the afterbay sill, reaching the fish lock entrance.

A comprehensive study conducted at the National Civil Engineering Laboratory of Portugal (LNEC) employed computational fluid dynamics (CFD) and physical modelling to optimise the system proposed by EDP. Velocity fields and flow depths across a range of operational scenarios were evaluated. A multidisciplinary team, comprising experts in hydraulic engineering, computational and physical modelling, and ecological science from LNEC, EDP, and MARE/University of Évora, worked in close collaboration, analysing the results, and recommending design optimizations.

1.3. Methodological Approach

In the past, complex hydraulic structures, such as fish pass systems, were solely evaluated using physical modelling, implying significant building and operation costs. Despite the scale effects and experimental limitations, this method delivers measurements of flow in critical areas.

Over the last 20 years, computational fluid dynamics (CFD) of hydraulic structures proliferated among researchers and practising engineers due to technological advances. CFD allows testing designs in a relatively short time, with significant cost savings. However, CFD models may have limitations in reproducing the most complex flows, or demand exorbitant computational resources, especially in the presence of aeration [9,10,11]. Studies highlight the effectiveness of CFD in evaluating fishways, particularly for analysing flow structures and improving hydraulic conditions [12].

An integrated approach of CFD and physical models may mitigate shortcomings of both and even potentiate each other, significantly reducing costs and promoting more design optimisation. Additionally, CFD simulations provide critical pre-analysis insights for the initial physical model setup, minimising physical trials, and improving efficiency. Hence, this combination is the most advanced and robust methodology for designing efficient and sustainable fish pass systems.

1.4. Importance of Interdisciplinary Collaboration

This project exemplifies the importance of interdisciplinary collaboration, involving experts in hydraulic engineering, computational and physical modelling, and ecological sciences.

Collaborative efforts ensure the fish pass system addresses both technical and ecological requirements of target location and respective fish species, integrating insights from regional and international case studies.

1.5. Structure of the Paper

This paper is structured as follows: Section 2 enumerates the objectives of the study, Section 3 presents the fish pass system description, and Section 4 outlines the methodology. Section 5 presents design stages and their assessments. Section 6 discusses the methods, and the workflow applied. The conclusions in Section 7 summarize key findings and recommendations for future applications.

2. OBJECTIVES

The primary objective is to validate and optimise the hydraulic performance of a new fish pass system, designed to enable migratory fish to access the future fish lock entrance, even during low water levels.

The secondary objective is to refine the methodology for integrating computational fluid dynamics (CFD) and physical modelling to evaluate large and complex hydraulic structures.

3. DESCRIPTION OF THE FISH PASS SYSTEM

3.1. Fratel Dam

The Fratel Hydroelectric Scheme (HS), operational since 1974, is the first on the Portuguese section of the Tagus River. It is located 32 km downstream of Spain's Cedillo HS and 21 km upstream of the Belver HS (Fig. 1). The reservoir has a total storage capacity of 93 hm³ and an active storage capacity of 21 hm³. The Belver reservoir is considered to extend upstream to the Fratel tailrace confluence with the Tagus River, significantly influencing the design and performance of the fish pass system. Table 1 summarises the characteristic reservoir levels of both reservoirs.

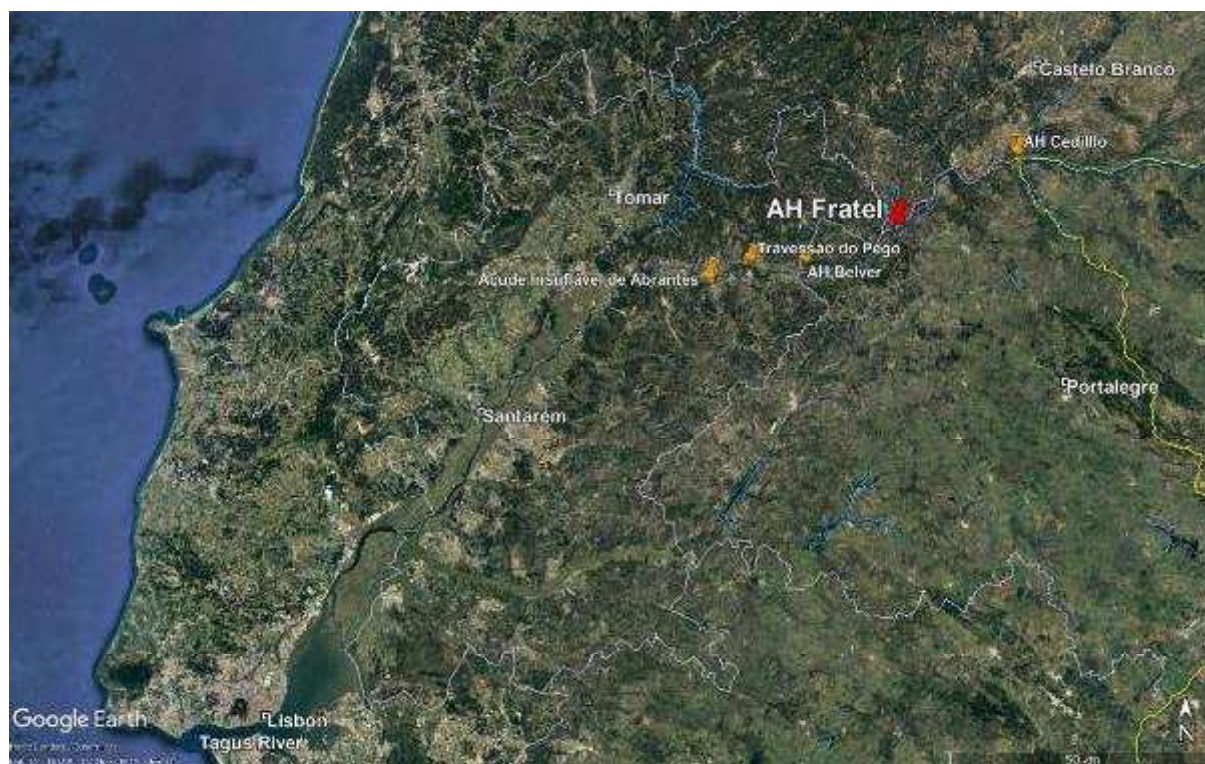


Fig. 1 – Location of the Fratel Hydroelectric Scheme and other cross-river structures on the Tagus River (Google Earth)

Table 1 – Reservoir characteristics levels for the Fratel and Belver Hydroelectric Schemes

Hydroelectric Scheme	Full Storage Level (m)	Minimum Operating Level (m)	Maximum Flood Level (m)
Fratel	74.00	71.00	76.00
Belver	46.15	44.00	47.15

The Fratel Hydroelectric Scheme consists of an overflow-dam on the right bank and separated by the central-wall, the hydraulic circuit of the generating units, the powerhouse, and the substation on the left bank (Fig. 2).

The spillway dam is a gravity-type concrete structure with a maximum height of 48 m and a crest length of 160 m extending to the central-wall. The dam crest is at elevation (78.00 m). The flood spillway has a maximum discharge capacity of 16,500 m³/s, and comprises six identical bays, each 18.75 m wide, with the crest at elevation (57.00 m). Energy dissipation is achieved through hydraulic jump dissipation basins.



Fig. 2 – Overview of the Fratel Hydroelectric Scheme from downstream [8]

The powerhouse is equipped with three generating units featuring vertical-axis Kaplan turbines, with an installed capacity of 132 MW and a nominal flow rate of 250 m³/s per unit. The static head ranges from 18 m to 29 m, and the turbine draft tubes' crest is at elevation (34.00). Immediately downstream, the afterbay consists of an ascending concrete ramp with approximately 60 m length and 50 m wide. The terminal section is a sill at the elevation (45.70), which includes six piers designed for the installation of cofferdams. Each pier has a cross-section 1.0 m wide, and the total clear span is 43.26 m (Fig. 3).

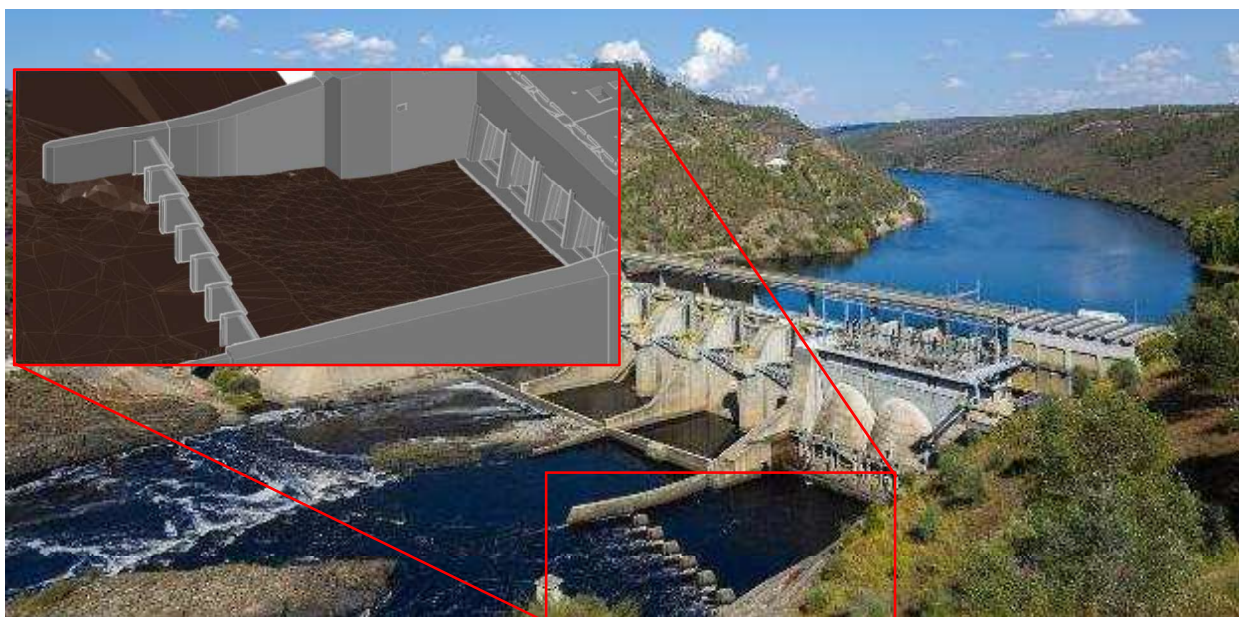


Fig. 3 – Central-wall, tailrace structure, including submerged area scheme (Source - File: CP 2240 Barragem de Fratel.jpg — <https://en.wikipedia.org>)

A fish lock entrance is positioned on the right side of the central-wall, in the afterbay (Fig. 4). The bottom of the entrance is 0.93 m higher than the afterbay sill, with the crest at elevation (45.70). Although the mechanical equipment was not installed during the dam's construction, operational assessments indicated that water levels suitable for the lock's operation would occur only 6% of the time annually [13].

Downstream of the afterbay, there is a rock-excavated channel with an irregular surface and an average elevation of (45.50), with 240 m long and 60 m wide. This channel follows the left bank, discharging the turbine outlets to the main riverbed. In the downstream extremity, there is a rock formation with an average crest elevation of (46.00), which functions as a ramp-weir with a length varying from 10 to 20 meters.



Fig. 4 – Fish lock entrance: view from the tailrace structure of the generating units [8]

3.2. Intervention motivation and scope

In 2025, EDP will initiate an intervention at the Fratel Hydroelectric Scheme on the Tagus River to improve power production efficiency and river connectivity, enabling fish access to upstream habitats. The operational head was increased 0.7 m by reprofiling the tailrace channel, which was widened, and its bottom lowered and levelled to (44.00 m). Priorly, with the average level at (45.50), it was occasionally dry, preventing fish from accessing the area downstream of the afterbay sill.

Subsequently, EDP analysed the impact of the reprofiling on facilitating migratory fish movement between the Belver reservoir and the Fratel dam, aiming to ensure access to the

entrance of the future fish lock in the afterbay, even during low water levels [13]. This led to the design of a new fish pass system, which is the focus of this study.

The design of the fish pass system is guided by the following key considerations:

1. The fish pass system will not function during periods of operation of the hydroelectric plant or flood spillways' discharge. In these scenarios, the maximum flow at the turbine outlets is approximately 10 m³/s, due to leakage, which is significantly lower than the discharge during turbine operation (200 m³/s to 600 m³/s). The fish lock contributes with an additional flow of 1 m³/s.
2. The level of the Belver reservoir, which extends to the Fratel tailrace channel, ranges between the minimum elevation (44.00 m) and the maximum elevation (46.15 m) and is a key factor in defining the solutions. The most frequent elevation is (45.00 m).
3. The afterbay sill crest, at elevation (45.70 m), creates an obstacle to fish movement. Lowering the sill is not feasible due to the minimum submergence requirements of the turbine units. A preliminary study suggested installing a fish pass device to resolve this issue, facilitating connectivity between the tailrace channel and the afterbay.
4. The channel bed of the reprofiled tailrace channel is at elevation (44.00 m), occasionally posing a limitation to fish movement, due to the lack of water depth. Therefore, constructing a dedicated fish channel excavated into the channel bed was considered to ensure connectivity, even during low water levels.
5. A monitoring campaign conducted in 2022 and 2023 identified the main target fish species to be considered in this study, concluding that native migratory species are mainly present in tributaries of the Tagus with lotic characteristics and downstream of Belver. In the case of the European eel, it was also found upstream of Belver HS. It was also concluded that there is a significant increase in the predominance of non-indigenous species in the most upstream stretches of the studied area.
6. Hydraulic performance criteria include velocities below 1.0 m/s throughout most of the fish pass system, with occasional maximums of up to 1.5 m/s along paths shorter than 2 m.
7. The installation of an efficient fish lock mechanism in the Fratel HS is critical for the success of the new fish pass system, providing effective access to upstream habitats necessary for spawning and other life stages, supporting the sustainability of aquatic ecosystems.

3.3. Initial design

The initial design of the new fish pass system is described below, and the design iterations are presented and analysed in Section 5 — Results (Fig 5).

The reprofiling of the tailwater channel involved lowering the average bed elevation from (45.50) to (44.00) and widening the bottom to 40 m, which allowed for an increase in the operational head by 0.7 m.

Additionally, the initial solution for the new fish pass system consists of four key elements, arranged from downstream to upstream, following the fish migration path:

- **230-Metre-Long Fish-Dedicated Channel**

- A fish-dedicated channel, 230 metres in length, with a trapezoidal cross-section featuring an upper width of 2.5 m and a lower width of 1.5 m, and a bed elevation at (43.00 m), excavated along the left side of the tailwater channel.
- This channel ensures hydraulic continuity along the tailwater channel, connecting the Belver reservoir to the downstream side of the afterbay sill, even when the reservoir is near its minimum value (44.00 m).

- **Four-Pool Fishway**

- A four-pool fishway, constructed in concrete, is 18.1 metres long, 3.9 metres wide, and 4.6 metres high. It is located on the right side of the afterbay sill, adjacent to the central wall that separates the powerhouse from the spillway. The top elevation of the external walls and internal baffles is (46.50 m).
- Each pool measures 4.0 m in length, 2.7 m in width, and 1.25 m in height, with a bottom slope of 5%, providing a resting area for fish. The vertical slots between pools are 0.4 m wide.
- Optimal operating conditions are achieved with a discharge of 1 m³/s and a total drop of 1.25 m, distributed across the three vertical slots between pools and the two slots at the entry and exit. Each drop has a height of 0.25 m.
- This fishway enables fish to overcome the maximum flow drop of 1.25 m between the tailwater channel (44.00 m) and the afterbay (45.25 m).

- **Afterbay Sill Bypass Channel**

- Located on the right side of afterbay sill, adjacent to the pool fishway, features a rectangular cross-section with a base width of 2.5 m and a height of 0.7 m, resulting in a crest at level (45.00). It starts in the sill crest and develops along the fishway (Fig. 6).

- Reduces the afterbay minimum level to approximately (45.25) and generates a fish attraction flow next to the fishway, and into the 230-meter-long fish-dedicated channel, using the turbines leaks discharge.
 - Designed to operate effectively within the water levels of the afterbay, ranging from (45.00 m) to (46.15 m).
 - Creates an alternative path for fish movement past the afterbay sill when water levels on both sides of the sill are similar. Under these conditions, the bypass channel ensures favourable flow velocities, compensating for the low discharge from the pool fishway.
- **Fish lock entrance**
 - Located in the afterbay, at the central wall, with a rectangular cross-section measuring 1.2 x 1.0 m (W x H) and a sill at elevation (45.25 m), recessed by 1.4 m.
 - Designed to allow fish access to the fish lock across all afterbay water levels, which range from (45.00 m) to (46.15 m).

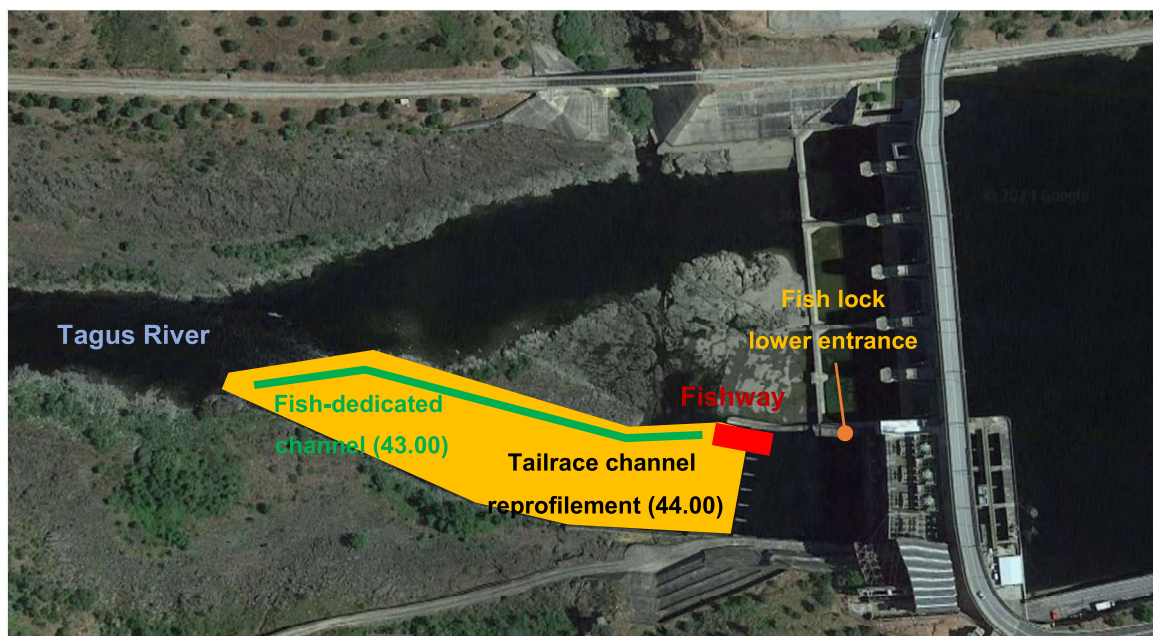


Fig. 5 – Initial design of the new fish pass system: top view (Source: Google Earth)

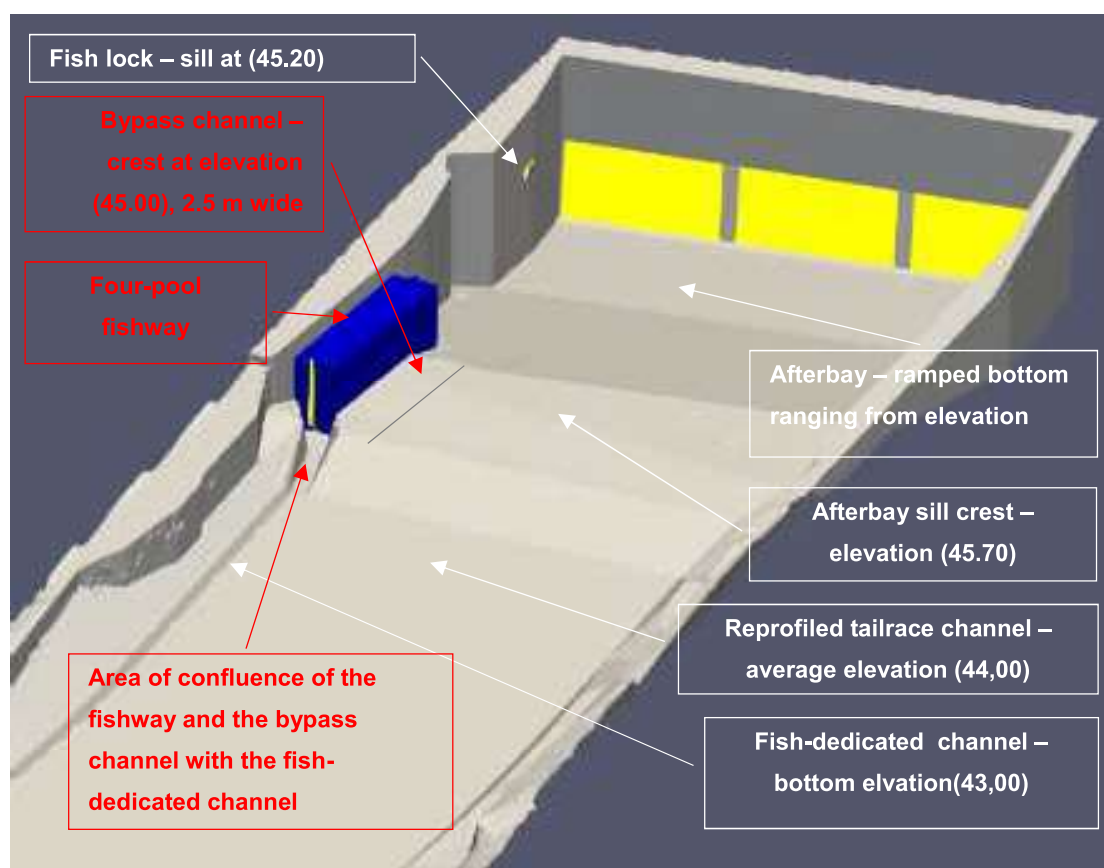


Fig. 6 – Initial design of the new fish pass system: 3D scheme of the afterbay

The downstream water level is dictated by Belver, ranging from elevations (44.00 m) to (46.15 m), while the afterbay is constrained by the sill's crest elevation (45.00 m).

Considering two paths for discharging flows from turbine leakage and fish lock operation past the afterbay sill (fishway and bypass channel), the design aimed to ensure suitable conditions for fish movement without significantly altering the afterbay water surface elevation. At low and intermediate Belver reservoir levels, fish are expected to use the fishway, as the bypass channel velocities are too high. However, for high levels in Belver, the fishway velocities decrease significantly, while the bypass channel velocities become more moderate, turning the bypass channel more effective by providing stronger fish attraction flows.

4. METHODOLOGY

4.1. Initial considerations

The hydraulic study of the new fish pass system at the Fratel Hydroelectric Scheme involves reproducing flow conditions between the afterbay and the tailrace confluence with the main channel of the Tagus River, covering an area of approximately 355 m by 90 m (Fig. 7).

Additionally, upstream and downstream sections of the confluence are included to define flow conditions accurately, such as water surface levels, resulting in a total domain length of 450 m.



Fig. 7 – The new fish pass system: area of interest. Source: Google Earth [13]

The large domain dimensions and low flow rates (4 to 10 m³/s), resulting in shallow flow depths (less than 1 m), would require an impractically large physical model, as detailed in Section 4.3. Similarly, developing a single computational model to accurately capture all geometries would be computationally prohibitive due to the wide range of time and length scales involved.

In 2018, EDP conducted a preliminary study on the reprofiling of the tailrace channel using two-dimensional modelling. However, at the present study, the geometries involved — primarily the fishway, the turbine dissipation basin, the lowered sill and its transition to the secondary channel, the secondary channel, and the confluence — indicated the importance of capturing the three-dimensional nature of the flow in these areas. Consequently, a three-dimensional numerical model was selected.

To address these challenges, the study adopted a dual approach combining CFD and physical modelling. This integration was essential for detailed testing of multiple design iterations, minimising the need for physical trials, and significantly reducing costs.

A multidisciplinary team comprising experts in hydraulic engineering, computational and physical modelling, and ecological science from LNEC, EDP, and MARE/University of Évora, worked in close collaboration. For each design iteration, the performance was analysed, identifying potential issues, and suggesting optimizations, until a good overall system performance was achieved.

Next, both modelling techniques are described following the order application, where the fish pass system analysis started from the global to the detailed analysis, i.e. from CFD to physical model.

4.2. Computational Modelling

Computational fluid dynamics (CFD) simulations were conducted to globally model the new fish pass system, considering the entire domain between the tailrace confluence with the Tagus River and the afterbay. Key elements were accurately reproduced, including the reprofiled channel and its confluence with the Tagus River, the 230-metre-long fish-dedicated channel, the afterbay with the three turbine circuit outlets, and the fish lock entrance flow. The pool fishway, however, was modelled indirectly.

The primary objective was to evaluate the hydraulic performance of the following elements:

- Tailrace channel
- 230-metre-long fish-dedicated channel
- Bypass channel at the afterbay sill

CFD provided critical pre-analysis insights and expedited design optimisation, before the construction of physical model, minimising physical trials.

Numerical modelling was performed using OpenFOAM v2012, a state-of-the-art open-source computational fluid dynamics (CFD) software (OpenCFD, 2020). The interFoam solver, designed for two immiscible and incompressible fluids (air and water), was employed due to the predominantly free-surface flow with negligible air entrainment. The solver uses the finite volume method to solve the Navier-Stokes equations, applying the URANS (Unsteady Reynolds-Averaged Navier-Stokes) approach with the realizable k-epsilon turbulence model. The free surface is captured using the VOF (Volume of Fluid) technique. Further details can be found in Mendes (2021).

OpenFOAM, and interFoam, have been successfully applied at LNEC to various types of free-surface flows, such as the spillways of the Fierza Dam in Albania [15], as well as in several scientific research projects on air-water turbulent flows [9,10,11].

The computational grids were primarily orthogonal, consisting of cubic elements, with few exceptions at the boundaries. The total number of cells was approximately 10 million, with a size of $0.25 \times 0.25 \times 0.125 \text{ m}^3$ (X, Y, and Z axes) for cells occupied by water. The vertical direction, associated with gravitational acceleration, was aligned with the Z-axis.

The following boundary conditions were applied:

- **Fish lock:** Uniformly distributed discharge and aligned with the internal geometry of the existing structure.
- **Turbine outlets:** Leakage discharge for each unit, uniformly distributed and perpendicular to the outlet section face.
- **Fishway:** Only inflow and outflow, uniformly distributed along the depth and perpendicular to the inlet and outlet faces of the fishway sections.
- **Concrete walls:** Equivalent sand-grain roughness height of 0.5 cm.
- **Terrain next to the fishway:** Including the turbine ramp and transition zone from the tailrace sill to the reprofiled channel, with an equivalent sand-grain roughness height of 5.0 cm.
- **Reprofiled terrain and Tagus River:** Equivalent sand-grain roughness height of 10.0 cm.
- **Downstream:** outflow/inflow adjustments according to the defined water surface level.
- **Top boundary:** volume continuity condition regulated by air inflow/outflow.

The following numerical schemes were used: Euler and local Euler (Local Time Stepping) for the temporal derivative; Gauss linear gradient, with and without multidirectional limiter, for the spatial gradient; Gauss upwind and Gauss linearUpwind for the velocity divergence; and Gauss upwind and Gauss limitedLinear for the turbulence fields.

In each simulation, it was monitored: total kinetic energy, turbulent kinetic energy, inlet and outlet flow rates, maximum velocity, maximum pressure, and water levels at eight locations. Simulations were run for the duration required to ensure steady-state conditions, particularly regarding the stabilization of water surface levels in the afterbay and at the confluence, as well as the outlet flow rate at the downstream boundary. The average computation time was eight days, using 64 processors. Simulations were carried out using resources from LNEC, integrated into the high-performance computing centre of INCD (National Distributed Computing Infrastructure).

4.3. Physical Modelling

The large domain of interest and the multiple hydraulic parameters requiring accurate similarity reproduction and measurements, such as very low velocities and flow depths in the reprofiled channel, would necessitate a physical model with a very low geometric scale factor (ideally

less than 5). This would result in an occupied area exceeding 70 m by 18 m, making it excessively costly and disproportionate to the new fish pass system construction cost.

The hydraulic phenomena are governed by gravitational forces, requiring adherence to Froude similarity (Fr) to establish dimensional relationships between the reduced model and the prototype, correlating gravity and inertial forces. For turbulent flows, the geometric scale must ensure Reynolds numbers (Re) of at least 10^4 in the model to maintain similarity with the prototype. Although a geometric scale of $L_r=7.4$ or lower was ideal, space constraints in the experimental laboratory limited the scale to $L_r=10$, resulting in a model Reynolds number (Re_m) of 0.63×10^4 , which is considered sufficiently close to the target $Re_m = 10^4$. Economic feasibility and space limitations were also factored into the scale definition.

Hence, a 1:10 scale physical model was developed to focus on the hydraulic behaviour of fish migration past the afterbay sill and the fish lock discharge attraction potential, allowing detailed flow analysis and further design refinements. It adequately reproduces the draft structures of the three turbine units, the afterbay, the fish lock discharge, the fishway, the bypass channel at the sill, and the initial segments of the reprofiled tailrace channel and the fish-dedicated channel (Fig 8).

The scaling relationships used in the study for the relevant quantities are as follows:

- Lengths (geometric scale): $L_r=10$
- Areas: $A_r = 10^2$
- Velocities: $V_r = 10^{1/2}$
- Flow rates: $Q_r = 10^{5/2}$
- Times: $t_r = 10^{1/2}$

The model occupies a laboratory area of 20 meters by 6 meters, with a height of 2.0 meters, and allowed for precise measurements of velocity fields, flow depths, and turbulence patterns.

Non-traditional construction methods, including CNC machining, 3D printing, and light and low-cost materials such as PVC sheets and EPS blocks, were utilised for the model's components. These components were assembled into a masonry structure consisting of two large reservoirs and a connecting platform (Fig 9).

The physical model includes four flow sources, replicating discharges from the three turbines and the fish lock, each regulated by installed valves for precise control. Downstream levels are controlled in a reservoir using exit valves.

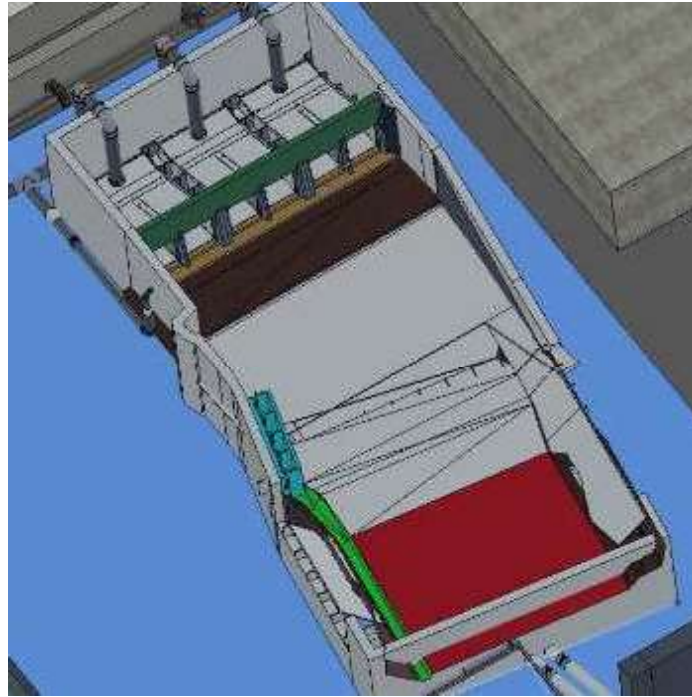


Fig. 8 – Physical model: 3D CAD scheme



Fig. 9 – Physical model construction.

The fish lock discharge system allows for adjusting the elevation of the rectangular entrance opening (1.0 m high by 1.4 m wide in the prototype) between (45.00 m) and (45.50 m) by replacing components manufactured using 3D printing. In the initial design, the new sill elevation for the fish lock entrance is set at (45.25 m).

The fishway, consisting of four successive pools separated by vertical slots, was mostly constructed using PVC sheets cut with a CNC machine. The more complex geometries of the vertical slots were produced in PLA via 3D printing (black elements in Fig. 8), as well as the turbine outlet piers.

Anticipating the need for future modifications in the bypass channel and 230 meters-long dedicated fish channel areas, these sections were constructed using expanded polystyrene (EPS) coated with a fibreglass-reinforced mortar (Figures 4.2 and 4.3 — grey surface).



Fig. 10 – Physical model construction: fishway and bypass channel

The measurements during the tests included flow rates, water levels, velocities, and flow direction. Flow rates were measured using electromagnetic and ultrasonic flow meters, while water levels were recorded with vernier point gauge in critical locations and graduated rulers near walls. Surface velocities were analysed using video processing with Matlab-PIVlab, and flow direction was qualitatively observed using dye tracers at the surface and wool threads near the bottom and within the flow.

4.4. Scenarios

The hydraulic performance of the new fish pass system was assessed for each design iteration, under multiple operating scenarios defined by varying water levels in the Belver dam reservoir, and turbine outlets. The criteria include **Hydraulic Continuity, Velocity Fields, and Flow Depths.**

The scenarios analysed comprise combinations of the following factors:

- **Geometry variations**, including the existing site and design iterations of the new fish pass system:
 - Before intervention
 - Initial design
 - Design A
 - Design B
- **Inflow discharges**:
 - Turbine outlet discharges: 0 m³/s, 3×1.0 m³/s
 - Fish lock discharge: 1.0 m³/s
- **Water levels** at the confluence of the tailrace channel and the main riverbed of the Tagus River, corresponding to three reservoir levels at Belver, selected based on non-exceedance probabilities for January to July, as determined by EDP:
 - Minimum level of (44.00 m), with a 1% non-exceedance probability
 - Intermediate level of (45.00 m), with a 46% non-exceedance probability
 - Maximum level of (46.15 m), with a 97.2% non-exceedance probability
- **Boundary conditions**:
 - Upstream: Defined by the imposed discharges from each turbine unit and the fish lock.
 - Downstream:
 - **CFD modelling**: Defined by the water level in the Belver reservoir.
 - **Physical modelling**: Defined by the water level estimated from numerical modelling at the downstream section of the physical model.

In the CFD calculations, the fishway was indirectly modelled by not replacing the pools with a discharge sink at the entrance and a discharge source at the exit, with a flow depth according to the surrounding water levels. The discharge values were set to 0.9 m³/s, 0.6 m³/s, and 0.0 m³/s for confluence levels of (44.00 m), (45.00 m), and (46.15 m), respectively.

5. RESULTS – CFD MODELLING

5.1. Initial considerations

Due to the large number of scenarios analysed, only the main results and the respective plots of velocity fields, and water surface levels of the final iteration are presented.

5.2. Before intervention

CFD simulations began with an analysis of the existing site. Additionally, a qualitative comparison was made between the flow from preliminary tests and a photograph of the site under similar flow conditions, confirming higher velocities and some air entrainment on the right side of the confluence (Fig. 11).

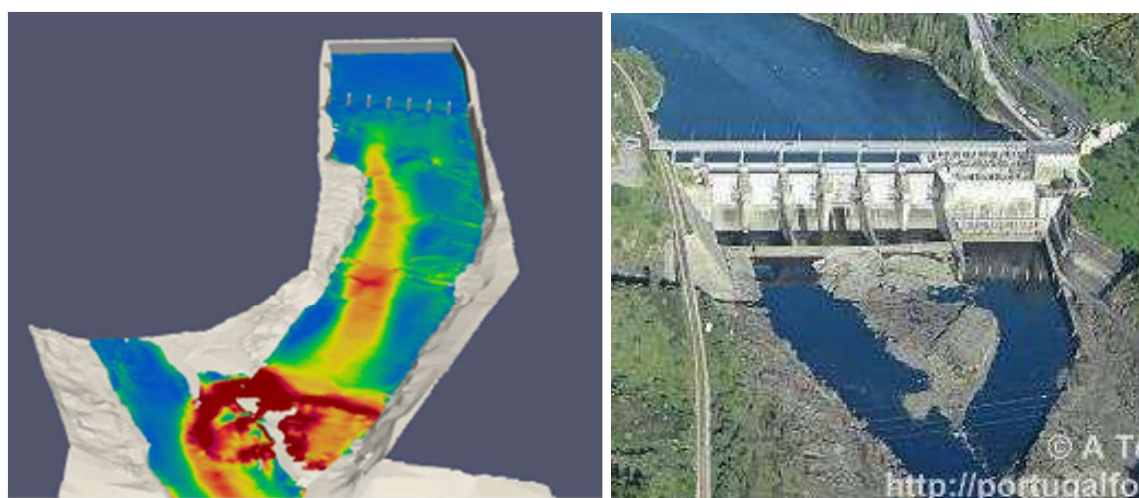


Fig. 11 – CFD model before intervention. Preliminary test: surface velocities and comparison with photograph. Leakage flow of 10.0 m³/s, confluence level (44.00 m). (source: <https://portugalfotografiaaerea.blogspot.com/2013/06/barragem-de-fratel.html>)

The simulations demonstrated similar hydraulic behaviour for confluence levels of (44.00 m) and (45.00 m) (Fig. 12, where the downstream section of the tailrace channel acts as a "control section", imposing subcritical flow upstream and creating localised and significant water drops. At the (46.15 m) level, the flow remains subcritical throughout the domain, controlled by the confluence level. the flow in the basin is identical for all three levels.

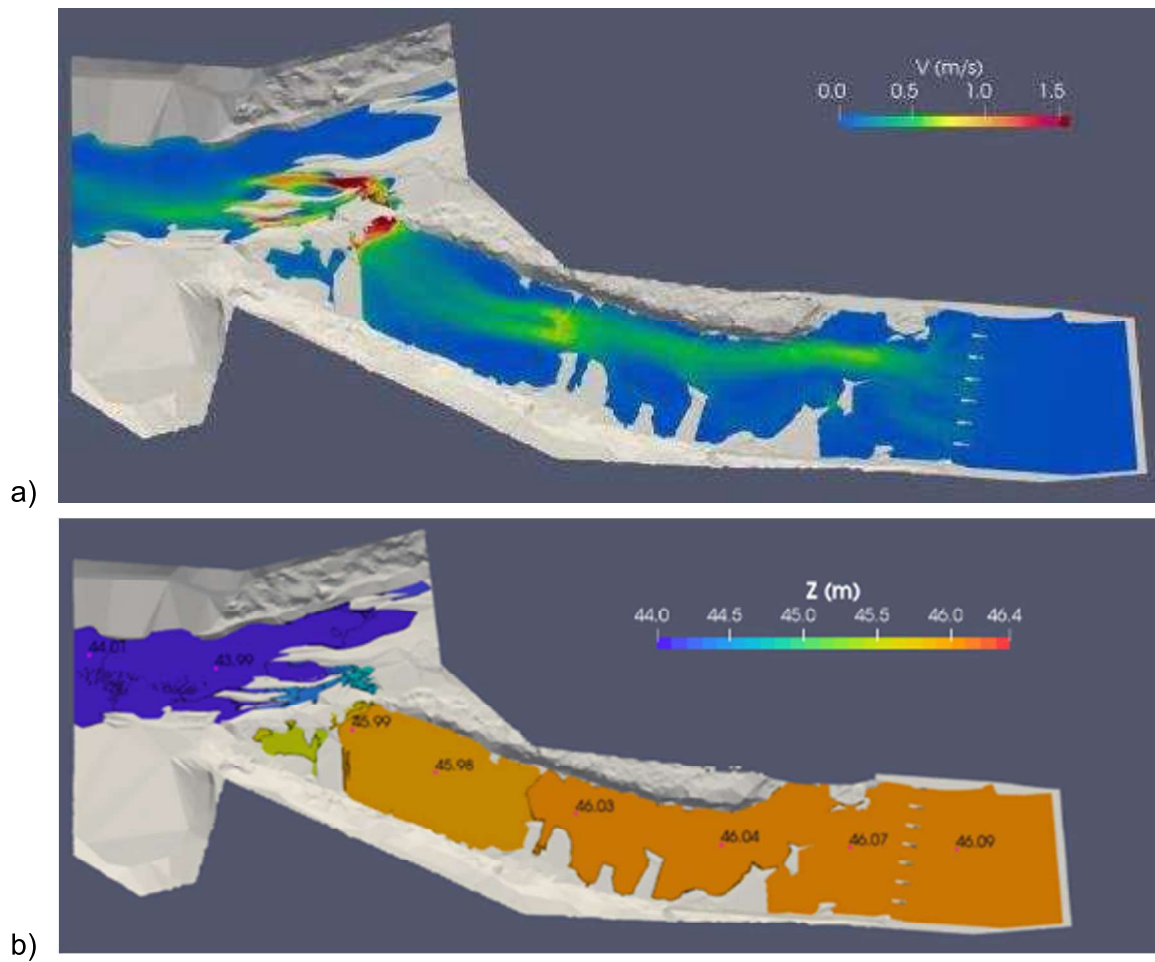


Fig. 12 – CFD model before intervention. Confluence level (44.00): a) Surface velocity field, b) water surface level.

5.3. Design iterations

Initial design

Preliminary tests based on the proposed design revealed distinct behaviours for the two analysed levels, (44.00 m) and (46.15 m), particularly regarding flow in the reprofiled channel. At a confluence level of (44.00 m), the flow along the reprofiled channel has a shallow depth of approximately 0.2 m and velocities around 1.0 m/s. The afterbay sill acts as a control section, imposing subcritical flow in the basin. At a confluence level of (46.15 m), the flow along the reprofiled channel has a depth of approximately 2.0 m and velocities below 0.2 m/s. The flow is subcritical throughout the domain, governed by the confluence level. Similar to before the intervention, the variation in free surface elevation across the studied domain is minimal, approximately 0.15 m from the confluence to the tailrace basin.

Design iteration A

This iteration incorporates improvements to the initial design, including the creation of a resting area downstream of the fishway and four resting zones along the secondary channel.

The analyses revealed that the resting zones along the secondary channel did not achieve the desired flow effects and required widening. The geometric definition of the reprofiling was also addressed, noting that excavation would involve blasting and ripping, resulting in a somewhat irregular geometry. Consequently, it was decided to add macro-roughness elements to the numerical model geometry in the excavated areas, instead of bottoms.

Design iteration B

The final stage of CFD modelling included the following design optimisations:

- Modifications to bypass channel, increasing its width from 2.5 m to 8.0 m.
- Changes to the bypass channel geometry in plan view.
- Extension of the resting zone downstream of the fishway.
- Introduction and refinement of the five resting zones in the fish-dedicated channel, with dimensions of 8.0 m in length, 2.0 m in width, and spaced 30.0 m apart.

The velocities and water surface plots for the three analysed levels are presented in Fig. 13 and Fig. 14.

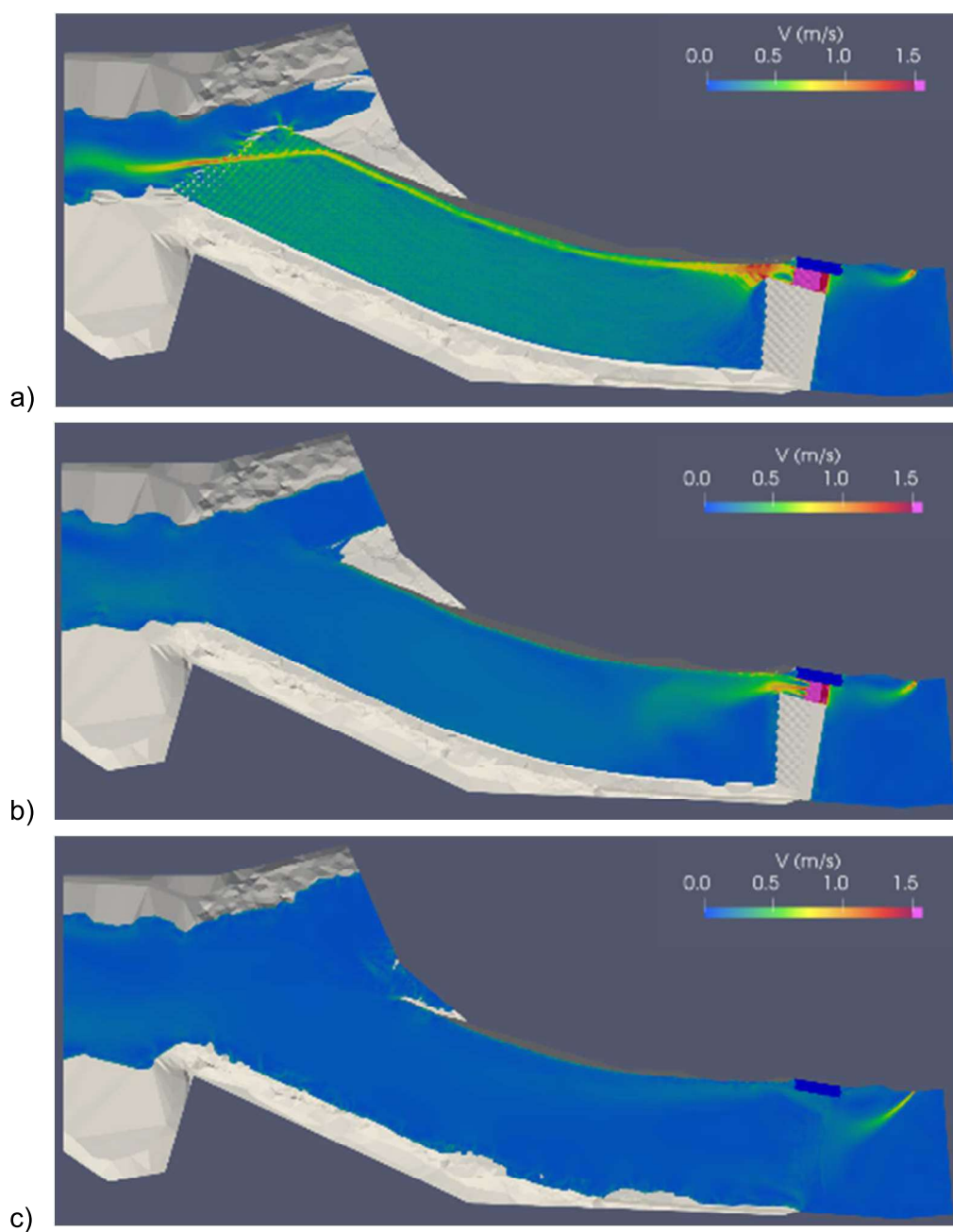


Fig. 13 – CFD final design: surface velocities. Confluence level: a) (44,00), b) (45,00) e c) (46,15)

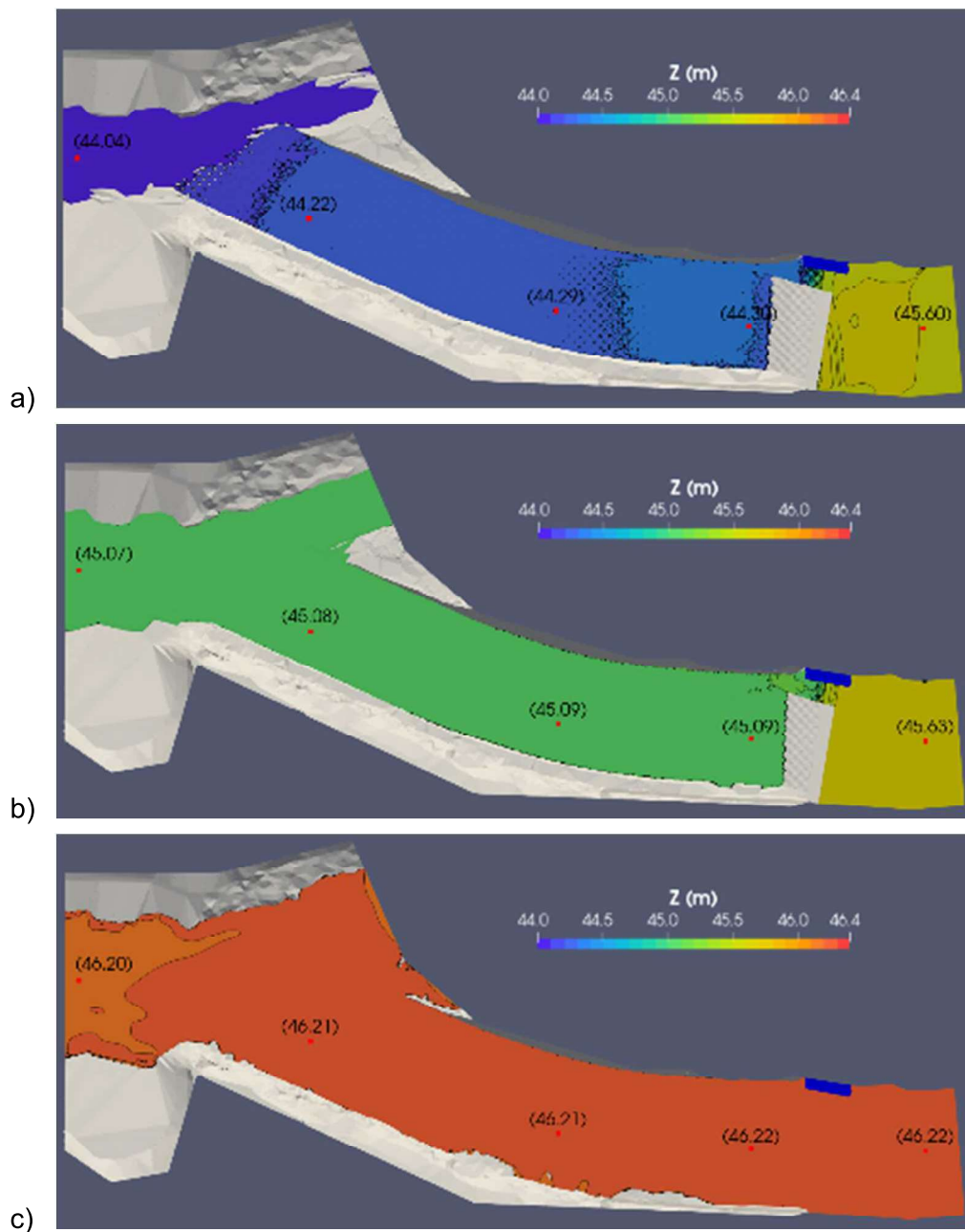


Fig. 14 – CFD final design: water surface level. Confluence levels: a) (44,00), b) (45,00) e c) (46,15)

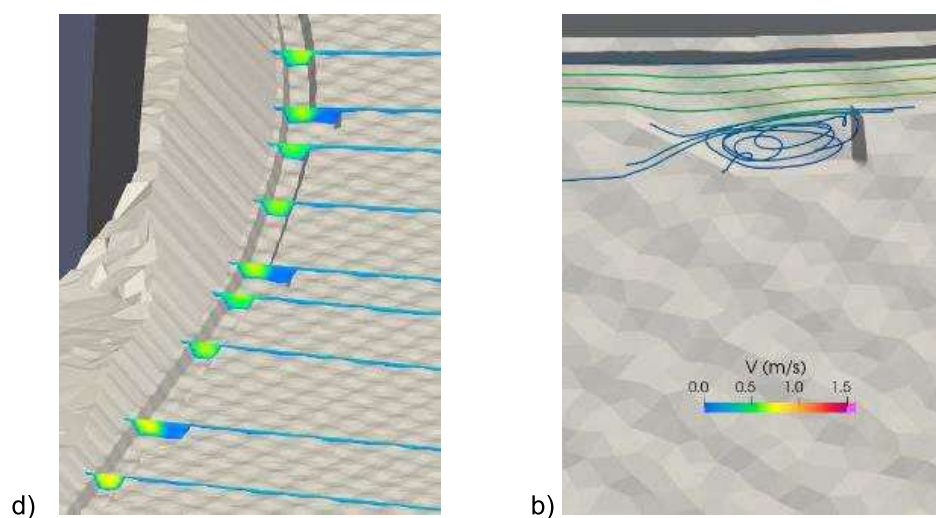


Fig. 15 – CFD final design: resting zones in the fish-dedicated channel: (a) velocity profiles in cross-sections, (b) streamlines. Confluence level (44.00 m).

The main iteration of the final design are presents in Fig. 16.

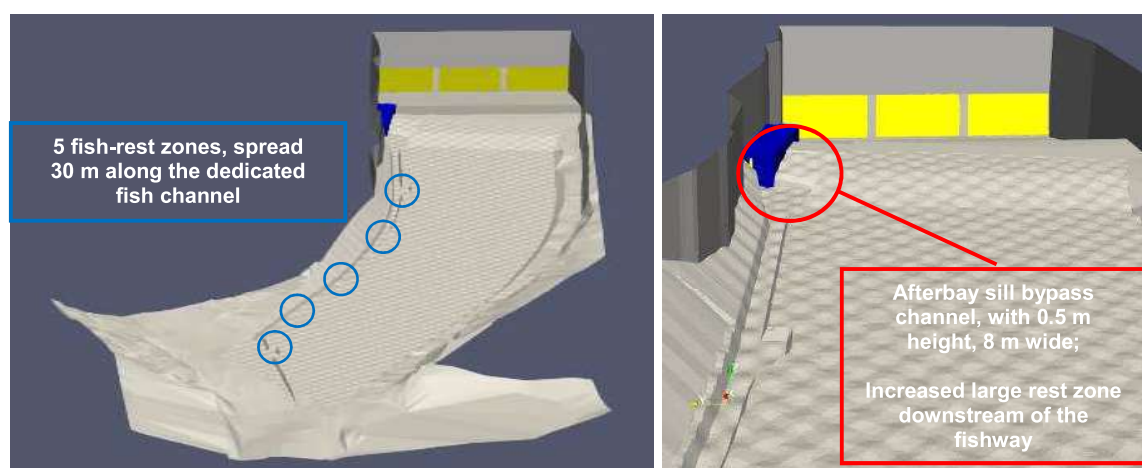


Fig. 16 – CFD final design: optimisations.

For all three scenarios, hydraulic continuity is maintained with depths not less than 1.0 m. Velocities exceed 1.0 m/s only near the lowered sill of the turbine basin, and the resting zones function as intended. Fish passage is possible via the fishway at all levels and via the lowered sill, particularly for confluence levels above (45.50 m), where the ramp becomes submerged, reducing velocities to below 1.0 m/s.

The reprofiling of the tailrace channel significantly improves hydraulic continuity, especially for Belver reservoir levels below (45.50 m), mainly due to the secondary channel, which ensures continuity at lower levels. This intervention homogenizes velocity distribution at the confluence

to below 1.0 m/s and eliminates water drops observed in before the intervention across all Belver reservoir levels.

5.4. CFD Benefits

The numerical simulations defined the configuration of the afterbay sill bypass channel and its transition to the fish-dedicated channel. They also determined the outflow curves for the downstream boundary of the physical model for the reproduced scenarios.

Numerical modelling contributed to improving the design, enabling the physical model to incorporate the proposed changes from the beginning of the trials.

The CFD modelling was based on the following assumptions:

- Simplified validation and calibration due to a lack of field data for the tailrace channel at the analysed flows and levels.
- Roughness geometry from reprofiling was simulated using custom algorithms, introducing regular patterns to approximate the random irregularities of rock excavation.
- The domain's large extent, from the tailrace to the confluence, limited resolution (maximum vertical resolution of 12.5 cm). Localised numerical modelling, including the fishway and lowered sill, was replaced by data from the physical model.
- The fishway interior was not numerically modelled; only inflow and outflow were considered, based on confluence levels.

6. RESULTS - PHYSICAL MODELLING

6.1. Initial considerations

In the physical model at scale 1:10, the fishway and turbine tailrace structures were fully reproduced.

The following program was established for the physical model trials:

- Preliminary tests to verify the general operation of the model and equipment.
- General characterisation of upstream water levels, including the vicinity and interior of the fishway and the lowered sill area.

- Velocity field characterisation in areas of interest, specially resulting of the fish lock discharge flow.

The physical model tests provided a general characterisation of flow conditions in the reproduced area, analysing three reservoir levels at Belver, along with additional intermediate levels. Detailed tests were not conducted for the (46.00 m) level, as the Belver reservoir extends to the central wall of the Fratel Hydroelectric Scheme in this scenario.

Visual inspection of flow conditions was complemented by qualitative tests using dye injected at key points to better understand flow patterns, velocity distributions, and turbulence levels, (Fig 17). Particle Image Velocimetry (PIV) technology was used to measure mean and surface velocity fields at the fish lock outlet, the fishway entry and exit zones, the fishway pools, the lowered sill area, and the downstream ramp.

6.2. Physical modelling trials

To keep the article concise, only selected results are presented next. The physical model tests started with the fish lock entrance sill at elevation (45.25 m). However, it was concluded that the lower sill elevation of (45.00 m) provides better pattern and intensity, hence, performance for the range of water levels in the turbine tailrace basin intended to ensure the fish lock's operation.



Fig. 17 – Physical model. Level (45.00). Horizontal jet from the fish lock into the turbine tailrace basin. Dye plume and surface PIV.

The pool fishway performed according to the design considerations (Fig. 17). The fishway and the lowering of the afterbay sill bypass channel ensure both hydraulic continuity for fish migration and adequate discharge conditions for flows from the fish lock and turbine leakage. Notably, the fishway is crucial for low to intermediate downstream water levels, maintaining flow depths above 1.0 m and velocities below 1.0 m/s.

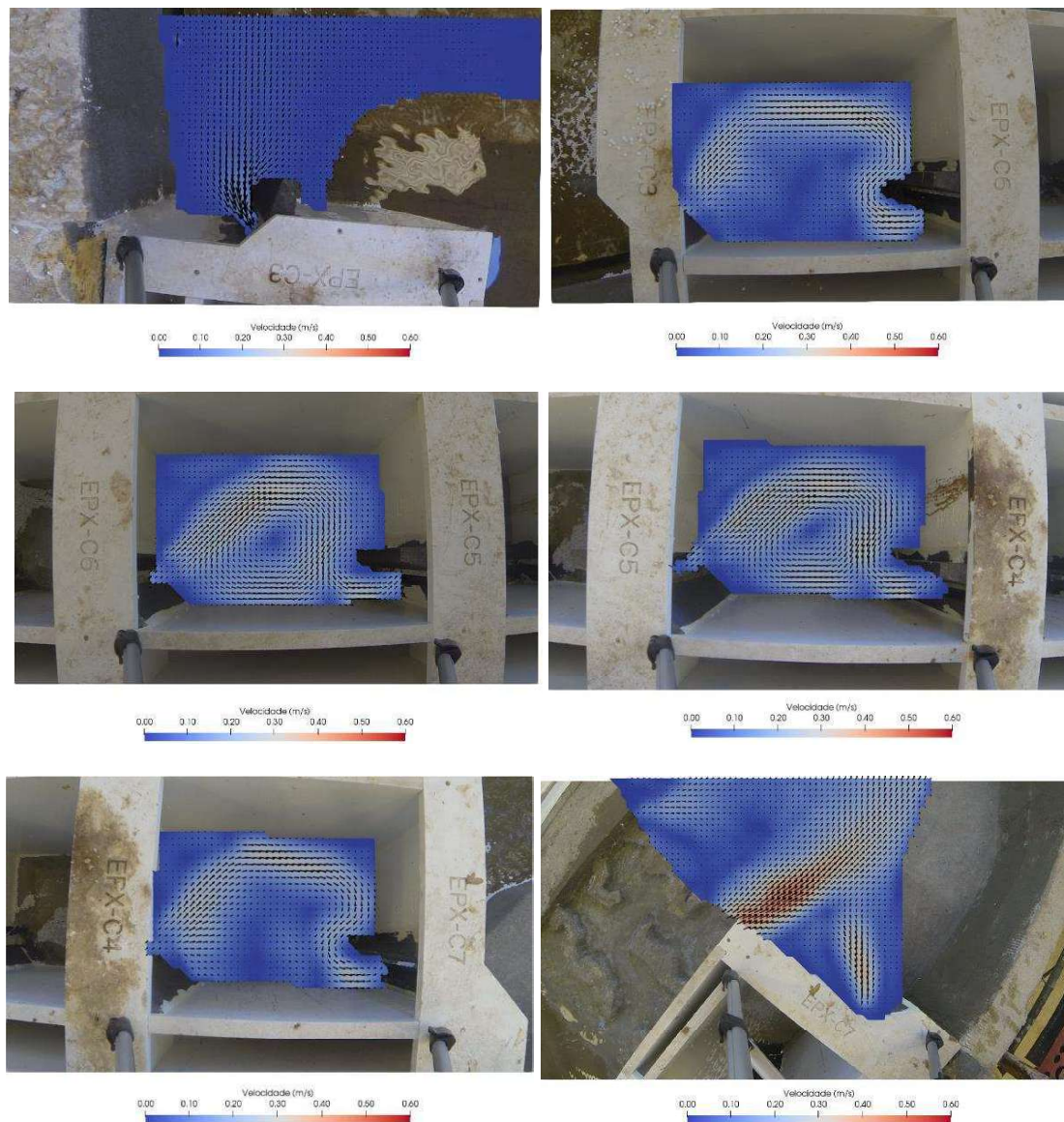


Fig. 18 – Physical model. Level (44.00). Pool Fishway. Time-average superficial velocities.
Sorted by: entrance, pools 1 to 4, exit.

Maximum velocities on the ramp reach approximately 4.0 m/s, but these are not uniform across the ramp width, with values around 1.0 m/s or lower on the right half. At the confluence of the ramp and the secondary channel, the maximum observed velocity is about 2.9 m/s. However, higher velocities are concentrated on the left side of the ramp and confluence, while much of the analysed area exhibits velocities below 1.0 m/s.



Fig. 19 – Physical model. Level (45.00): Lowered sill and connecting ramp to the secondary channel. Dye plume released upstream of the flow control sill.

Despite the results of the CFD modelling, an enhancement to design iteration B was proposed: incorporating macroroughness elements on the bypass channel downstream of the lowered sill. These elements would act as obstacles to the fast flow occurring on the ramp at intermediate or low water levels in the Belver reservoir, creating flow conditions more similar to those observed in nature. Due to limitations in mesh resolution in this area of the numerical model, the effect of introducing macroroughness was studied exclusively in the physical model.

Following the hydraulic characterisation of Design iteration B from the numerical model studies, additional tests examined the hydraulic performance with macroroughness elements on the bypass channel ramp between the lowered sill and the large resting area downstream of the fishway. Two geometries for these obstacles were tested, both provided by EDP. The first iteration was based on general guidelines from MARE/UE biologists, while the second iteration refined hydraulic performance observed in the first.



Fig. 20 – Physical model. Level (45.00). Bypass channel ramp:

a) flat bottom; b) macroroughness.

The addition of macroroughness elements on the bypass channel ramp downstream of the sill crest, which is lowered from the current elevation (45.70 m) to (45.20 m), improves hydraulic performance, particularly for the most frequent operating conditions corresponding to Belver reservoir levels near elevation (45.00 m).

Overall, for the most demanding and less frequent scenario of Belver's, the minimum storage level (44.00 m), and the more frequent scenario (45.00 m), the velocity fields and water depths are according to design criteria. The optimal hydraulic performance of key components was attained, particularly the fishway interior and vicinities, as well as the downstream rest area in the confluence with the 230-meters-long dedicated fish channel. These structures ensure effective flow along the two preferred paths, through the fishway and along the ramp downstream of the lowered turbine tailrace sill, providing migratory fish access to the afterbay, and consequently to the fish lock entrance.

7. DISCUSSION

The results from both numerical and physical modelling provided a comprehensive a hydraulic characterization, including velocity fields and flow depths, under various operating scenarios dictated by the water levels in the Belver reservoir, downstream of Fratel HS. The analysis

focused on the hydraulic performance of the fish pass and ensuring hydraulic continuity between the powerhouse afterbay and the tailrace.

CFD provided critical pre-analysis insights and expedited design optimisation, before the construction of the physical model, bypassing several design iterations, and minimising physical trials, further improving efficiency. Moreover, it set up an advanced design to be further developed, with focus on localized issues. The physical modelling allowed a more detailed analysis in more complex parts of the domain.

The study underscores the value of integrating numerical and physical modelling in hydraulic engineering projects. The collaborative approach ensured that the fish pass system met ecological objectives and target fish species requirements, while adhering to hydraulic and structural constraints. This methodology provides a blueprint for designing eco-friendly dams that balance energy production with environmental stewardship.

By leveraging an advanced combined modelling approach and interdisciplinary collaboration, the project achieved:

- Enhanced ecological connectivity for migratory fish.
- The integration of environmental and ecological considerations into dam, and respective operation, design.
- An efficient modelling methodology regarding time, costs, allowing multiple design optimisations in a short period of time, including a development of the solution during the phases of conception and construction of the physical model
- Insights into the practical application of numerical and physical modelling in complex hydraulic systems.

Nevertheless, posterior CFD model validation, using the physical model data, could be performed. Effectively, CFD simulations of the localized domain, both on laboratory scale (1:10) and prototype scale, could share insights on the ability of CFD replace some physical trials, and advance the capacity of extrapolation of CFD results to the prototype.

8. CONCLUSIONS

A comprehensive study conducted at the National Civil Engineering Laboratory of Portugal (LNEC) employed computational fluid dynamics (CFD) and physical modelling to optimise the new fish pass system of Fratel Hydroelectric Scheme. Velocity fields and flow depths across varying operational scenarios were evaluated.

The final design was considered adequate to allow migratory fish to move between the river and the powerhouse afterbay sill, even during low water levels, and reach the entrance of a future fish lock, which is expected to enable access to upstream habitats. The key elements

are a 230-metre-long fish-dedicated channel, dug along the tailrace, with five resting areas, a four-pool fishway, and a bypass channel with irregular baffle walls.

The combination of CFD and physical modelling proved essential to deal with the large domain and the range of spatial and time scales, avoiding an unfeasible large physical model, and exorbitant CFD calculations. This integrated approach significantly reduced costs and expedited design optimisation, bypassing several design iterations, and minimising physical trials. Additionally, CFD simulations provided critical pre-analysis insights for the initial physical model setup, further improving efficiency. The results from both methods provided a comprehensive hydraulic characterization, including velocity fields and flow depths, under various operating scenarios.

The project's success was driven by the advanced modelling and the collaboration of specialists in hydraulic engineering, computational modelling, and ecological science from EDP, LNEC, and MARE/University of Évora. This interdisciplinary effort ensured that ecological and hydraulic objectives were seamlessly integrated, demonstrating the critical role of collaboration in advancing eco-friendly infrastructure.

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