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The Use of a Multi-Criteria Decision Analysis Method to Select the Most Favourable Type of Fish Pass in Mountainous Areas

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Abstract: Fish passes are a key element enabling the migration of aquatic organisms in the context of restrictions resulting from the presence of weirs. Multi-criteria decision analysis, AHP, and Rembrandt methods were used to assess the effectiveness of fish passes on mountain rivers. Three common types of fish passes were considered: slotted fish pass, block ramps, and a circulation channel with boulders. The results of the study indicated that block ramps proved to be the most favourable solution, achieving the highest preference values in both methods (Rembrandt: 0.77, AHP: 0.63). The key factors influencing the effectiveness of the fish passes are the availability of space and the water requirements, which reached values of 0.38 and 0.27 in the Rembrandt method and 0.33 and 0.28 in the AHP method, respectively. The differences between the results of both methods were minimal and did not have a significant impact on the final choice. The discussion emphasised the advantage of nature-like fish passes, such as block ramps, which better preserve the ecological continuity of rivers and can be more easily adapted to local hydrological conditions. The study also indicated the need for continuous monitoring of the fish passes and their optimisation to reduce problems related to sedimentation and flow blocking. The obtained results can provide a valuable basis for decision making in the planning and construction of fish passes, especially in demanding mountainous conditions, contributing to improving the effectiveness of fish migration and minimising negative impacts on the natural environment.

Keywords: fish passes; multi-criteria methods; block ramps; mountain rivers

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1. Introduction

The construction of dams results in the restricted movement of aquatic organisms and a change in their living conditions [1,2]. These restrictions can be reduced by the construction of fish passes, which facilitate the upstream or downstream migration of various aquatic organisms.

Modern environmental management requires increasingly advanced tools and methods that allow for the sustainable use of resources while minimising the negative impact on ecosystems [3–6]. One such tool is the Multi-Criteria Decision Analysis method, which is widely used in various fields, including water planning and management [7–9]. A particular challenge is the selection of the most favourable type of fish pass in mountainous areas, where the diverse hydrological and geomorphological conditions and biological richness require detailed analyses and an appropriate approach [10]. Fish passes are structures enabling the migration of fish and other aquatic organisms through hydrotechnical obstacles, such as weirs or dams. Their effectiveness depends on the type of fish pass, the operating conditions, and the potential impact on local ecosystems.

The currently fashionable and recommended fish passage structures, if spatial or technical conditions (difference in level, amount of water) allow, tend towards "nature-like" solutions (with boulders and plants), but sometimes the only possible solution is compact technical fish passes. However, it should be clearly emphasised that efforts aimed at preserving "ecological corridors" in rivers, including the selection of the optimal type and then the design and construction of effectively operating fish passes, is a difficult and complex issue that requires expertise from many scientific disciplines. The selection of the appropriate type of fish pass is a complicated process that requires taking into account numerous criteria, such as ecological efficiency, costs, durability, operational and landscape issues, and social acceptance [11].

The proper functioning of fish passes depends on many local factors, including ensuring that the water stream is appropriate and will attract fish, the design of the entrance and exit, ensuring that the location of the fish pass is easy for aquatic organisms to find, and ensuring the appropriate depth and velocity of water in the fish pass [12–14]. Not all parameters related to the proper operation of the fish pass are beneficial from the point of view of the operator of the hydrotechnical structure [15,16]. Particular attention should be paid to the amount of water consumption required for the proper operation of the structure, the cost of its construction, and its ease of operation [17].

In the channels of conventional technical fish passes, there are often barriers equipped with holes, slots, and various equipment to create flow conditions in which fish are able and willing to move both upstream and downstream. Conventional fish passes are usually constructed of concrete, metal, or wood. In contrast, nature-like fish passes reproduce natural river channels, both in terms of the hydraulic conditions of the flow and the natural materials used in their construction, such as boulders, rocks, gravel, tree trunks and branches, and vegetation. They imitate natural block ramps or pools and troughs to an extent similar to real conditions [18]. They are intended to provide the appropriate environmental aspects of a passage for a wider range of fish species than fish passes designed for specific target species [19]. Natural fish passes are particularly suitable and useful for obstacles of low or medium height, ranging from a few centimetres to a few metres [19].

In recent years, there have been significant advances in fish pass technology, particularly in the use of artificial intelligence (AI) [20]. These tools allow for the automated monitoring of fish migration, optimisation of fish pass performance, and improvements in decision making processes for waterway restoration projects. The introduction of AI-based methods enables more precise fish pass designs and their adaptation to the specific ecological needs of a given area, which enhances the effectiveness of riverine ecological continuity restoration [21]. Decisions regarding river restoration and the construction of fish passes are increasingly being supported by advanced decision-support systems. The integration of hydrological, ecological, and socio-economic data allows for the more sustainable management of restoration projects, while also taking environmental protection aspects into account [22]. In such systems, analytical tools, such as multi-criteria decision analysis (MCDA) and optimisation models, help in selecting the most effective solutions while minimising negative impacts on ecosystems [10].

Analytic hierarchy methods involve comparing the recorded pairs of criteria and decision variants, in accordance with the assumptions of each method, on a multi-criteria tree [22,23]. Examples of this type include the AHP and Rembrandt methods [24,25]. The SAW method is an example of an additive method that uses a linear function to model the decision-maker's preferences [26]. In the PROMETHEE methods, a preference function is developed for each criterion, which allows for the strength of preferences to be measured. Methods from the ELECTRE family aim to reproduce, as realistically as possible, the decision problem under analysis by introducing equivalence and preference thresholds [27,28].

Individual parameters are closely related to the types of fish pass. The basic division of structures distinguishes technical, semi-natural, and atypical fish passes. Each of the

mentioned types has advantages related to the preferences of the structure administrator or the needs of migrating aquatic organisms [29]. Thus, the selection of the best type of fish pass should be preceded by detailed analyses taking into account the previously mentioned factors.

In recent years, many scientific works have appeared in the literature that analyse different approaches to the assessment and selection of fish passes using multi-criteria methods [30,31]. These studies show the advantages of using these methods in the context of environmental protection and the sustainable management of water resources [32–34]. Methods such as AHP (Analytic Hierarchy Process) or PROMETHEE (Preference Ranking Organization METHOD for Enrichment Evaluation) enable the comprehensive analysis and comparison of various options, taking into account both quantitative and qualitative criteria [35–37].

Fish passes in mountainous areas are characterised by certain features that are difficult to observe in the case of structures located in lowlands. Above all, damming in mountainous and submontane areas is much greater, which affects the size of the fish passes (the number of chambers and length of the passes, and, therefore, the area the fish pass will occupy). The accessibility of the terrain is also fundamentally different due to its topography and geological structure. The composition of the ichthyofauna of these rivers is also obviously different, as are the needs of the fish in relation to the design and dimensions of the fish pass [38]. From the administrator's point of view, the risk of silting up the fish pass and the deposition of plant debris is also important, especially during flood events [39,40]. For these reasons, among others, the selection of the optimal solution for fish passes located in mountainous and submontane areas is extremely important for the investor.

In mountainous regions, fish passes play a crucial role in maintaining the ecological continuity of waterways. These structures are particularly important for fish species, such as salmon and trout, which require access to mountain spawning grounds. Fish passes not only improve the migratory capabilities of fish but also contribute to the restoration of river ecosystems by enhancing the habitat conditions and biodiversity within river channels [41]. Consequently, they strengthen the food web and support ecological processes such as nutrient cycling [42].

In this study, two methods were used to select the most favourable type of fish pass: the AHP and Rembrandt. The three most common fish pass solutions were analysed: a slotted fish pass, a circulation channel with boulders, and block ramps for fish.

The types of fish pass selected for our study are considered the most representative of their group [29]. The general classification of fish passes [38] includes three main groups of these devices. These are as follows: (1) engineered fish passes, (2) seminatural ("close to nature") fish passes, and (3) specialty fish passes (e.g., fish elevators). Slotted fish passes are considered one of the most popular and effective technical fish passage solutions. However, modern trends in the construction of fish passes are moving towards "close to nature" solutions. These are usually various types of ramps that simulate natural rapids (block ramps for fish) and bypass channels (bypass channels with boulders), which resemble mountain streams in their appearance.

The innovation of this article is the use of multi-criteria decision support methods to analyse different types of fish passage in mountainous areas. Previously published articles indicate the use of AHP and Rembrandt methods for various purposes. I have not found any example in the literature of the application of multi-criteria methods to the selection of fish passages in mountainous areas. The obtained results can provide valuable guidance for the planning and construction of fish passes, contributing to improving their effectiveness and minimising any negative impact on the natural environment. The influence of the calculation method on the obtained results was also checked. This allowed for the recommendation of multi-criteria decision analysis methods for selecting the most appropriate solution to ensure continuity of flow for all migrating organisms in the river. Block ramps were indicated as the most adequate solution in the case of mountain rivers. The discussion of the results provides additional arguments supporting this solution.

2. Materials and Methods

2.1. Types of Selected Fish Passes

The study analysed three types of fish passes that were located in various water structures. The analysis of their functioning was intended to show the possibility of using multi-criteria methods to support decisions on the selection of the optimal construction solution and the design of water barrages that could ensure the ecological continuity of river ecosystems. Currently, there are many known fish pass solutions. The simplest criterion divides fish passes into technical and semi-natural ones. Each of these types has its advantages and disadvantages, which, in the tested multi-criteria methods (AHP and Rembrandt), are related to the factors analysed at level II of the hierarchical tree.

Semi-natural fish passes, an example of which includes block ramps, simulate the natural characteristics of the water stream in the river. They enable the provision of appropriate migration conditions for a wide range of flows and many species of aquatic organisms at various stages of development [19]. They are characterised by their ease of construction, low operating and construction costs, and aesthetic fit with the landscape. A higher flow volume is needed for their proper operation, which reduces the amount of water that can be used, for example, to generate electricity. Depending on the choice of location for the semi-natural fish pass, different problems can be presented. The disadvantages of semi-natural bypass fish passes include the need to select an appropriate shape, bottom slope, and material from which they will be made. Space is also needed to integrate the bypass into the area adjacent to the damming structure. A particular problem with poorly designed bypasses in the event of the intensive transport of sediment may include silting of the fish pass channel. Another issue is ensuring a continuous water stream that will attract aquatic organisms at the lower position of the water structure and the location of the outlet, which is close to the main stream of the water barrage. It should also be noted that it is necessary to ensure it is possible to regulate the amount of water entering the fish pass.

Therefore, considering these disadvantages of bypasses, solutions in which the fish pass is integrated with the damming structure are more favourable, an example of which is the block ramps shown in Figure 1. The block ramp on the Biała Tarnowska River is located along the entire width of the channel. This allows aquatic organisms to use various migration routes that were prepared during the construction of the structure. The fish pass is characterised by its having no problems related to the need to create appropriate conditions at the inlet and outlet. It also has fewer operational problems. The low water flow rates allow all aquatic organisms to move within the structure.



Figure 1. Honeycomb cascade-type block ramp on the Biała Tarnowska River in Grybów.

Figure 2 shows a slotted fish pass located at Kozielno Reservoir on the Nysa Kłodzka River. Slotted fish passes are very favourable in terms of water requirements, the amount of area occupied, and their integration with the barrage. However, they can be more easily silted up by flowing plant debris or sediment [39]. A slotted fish pass is characterised by a higher water flow velocity than semi-natural fish passes. This is due to the fact that the individual chambers are connected by narrow slots in which the velocity can reach up to 1.5 m/s. Therefore, some aquatic organisms are unable to use this type of structure to facilitate migration. The analysed fish pass (Figure 2) is located next to the hydropower plant in such a place as to ensure a fish-attracting water stream. Unfortunately, at low flows (so-called droughts), there may be problems with generating an attracting water stream of sufficient power.



Figure 2. Slotted fish pass at Kozielno Reservoir on the Nysa Kłodzka River.

A circulation channel with boulders is a combination of a technical fish pass and nature-like fish passes. In this fish pass, a sequence of pools has been created in a concrete channel, separated by block ramps made of artificial rocks, the width of which is adjusted by rotating the block ramps. The hydraulic conditions of the water flow are similar to those in a natural mountain stream. The design of the steps in the form of block ramps results in better energy dissipation in the fish pass, which facilitates the migration of weaker individuals, and by varying the design of the block ramps it is possible to influence the velocity values in the fish pass pool. Another advantage of this structure is the self-cleaning of the fish pass during floods, as well as the fish pass occupying a much smaller area than typical semi-natural fish passes. It also enables the two-way migration of all aquatic organisms, including bottom fauna. The circulation channel with boulders is particularly sensitive to changes in the headwater level. For this reason, a special structure, the so-called control section, should be built on the upper position to regulate the water flow [43]. It is also characterised by a good attracting water stream that can be found by fish. Figure 3 shows a photograph of the analysed circulation channel with boulders on the Nysa Kłodzka River in Nysa.



Figure 3. Circulation channel with boulders at Nysa Reservoir on the Nysa Kłodzka River.

2.2. Use of Multi-Criteria Methods

The study selected the best type of fish pass for mountain rivers using multi-criteria decision analysis methods. Multi-criteria methods are particularly useful for solving problems in which the selection criteria include both qualitative and quantitative factors. The method described by Saaty [23,28] has been developed by many researchers [36,37], enabling the solution of deterministic, stochastic, and fuzzy problems. The analyses used the Rembrandt and AHP methods, which facilitate the selection of the best solution when many factors need to be taken into account.

Problem-solving using multi-criteria methods is conducted in several steps. The first is to create a hierarchical structure, i.e., to decompose the analysed problem [34]. The hierarchical tree structure describes the goal, the general factors, and at subsequent levels, increasingly specific factors. The levels of the tree structure in the AHP method can be infinite, but there are always solutions at the last one. The tree structure shows the structure of the discussed issue in a comprehensive and clear way. The applied method for the assessment of the best fish pass solution for mountain rivers should be based on the AHP and Rembrandt methods. In the AHP method, the analysis is carried out according to Saaty's (1994) 9-point scale. The Rembrandt method is a response to the limitations of using the AHP method related to the rating scale, the method of calculating the value of the variant assessment, and the situation where a new variant is introduced into the ranking. In this method, Saaty's scale is replaced by a logarithmic scale [44]. The determination of the solution using the Perron–Frobenius eigenvalue method is replaced by the logarithmic least squares method [45].

The study addressed the results of an expert panel in which respondents assigned weights comparing the individual factors and elements of structures. The panel brought together experts—specialists (about 30 people) involved in the design, construction, and operation of fish passes. This enabled an efficient analysis of the problem under study. During the panel meetings, very heated discussions took place, which allowed for a broad look at the analysed problem. The knowledge of the experts made it possible to hierarchise

the problem of selecting fish passes, assign weights in the context of various priorities, and ultimately select the best fish pass solution. The numbers obtained in this way filled the matrices, the solution of which allowed for the importance of each element for the assessment of the best fish pass solution to be determined. This was to be used to determine the order of priority of the individual elements subject to assessment.

The analysed problem was described using a tree consisting of three levels (Figure 4). Level I describes the purpose of the analysis; level II is characterised by the defining factors describing a given problem; level III includes solutions to the problem. In multi-criteria analyses, factor comparison matrices were solved. The matrices were completed on the basis of a comparison scale from 0 to 8. Table 1 presents a descriptive summary of the comparison values of individual factors/solutions.

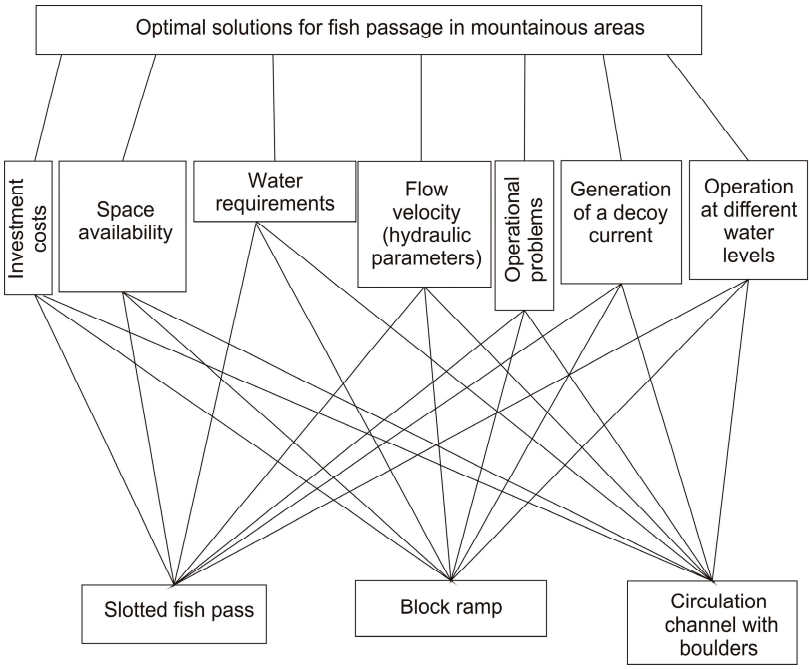


Figure 4. Hierarchical tree of the multi-criteria decision analysis method.

Table 1. Weights in the Rembrandt and AHP hierarchy analysis methods.

No.	Comparative Assessment	Rembrandt	AHP
1.	Very strong advantage between factors C_i and C_j	−8	1/9
2.	Strong advantage between factors C_i and C_j	−6	1/7
3.	Clear advantage between factors C_i and C_j	−4	1/5
4.	Slight advantage between factors C_i and C_j	−2	1/3
5.	Balance between factors C_i and C_j	0	1
6.	Slight advantage between factors C_i and C_j	2	3
7.	Clear advantage between factors C_i and C_j	4	5
8.	Strong advantage between factors C_i and C_j	6	7
9.	Very strong advantage between factors C_i and C_j	8	9

At level II, there is one matrix that is solved only once. At level III, a matrix is created which is then solved as many times as there are factors at level II. The matrix is solved using local vectors, which are then converted into global vectors, which enable the determination of the best solution. When selecting the optimal fish pass solution, parameters related to water requirements, water flow velocity in the fish pass, operational problems, the possibility of generating an attracting water stream, the efficiency of the fish pass at various water levels, and the impact of the transported material in the river were taken into account (Figure 4).

The analysed structures were the fish passes located on the Nysa Kłodzka and the Biała Tarnowska Rivers. Three types of fish passes were analysed: a slotted fish pass, a circulation channel with boulders, and a rock block ramp.

3. Results

Based on the analyses carried out using the Rembrandt method and information on the functioning and operation of the fish passes, a summary of the global vector results for level II of the hierarchical tree is presented in Figure 5.

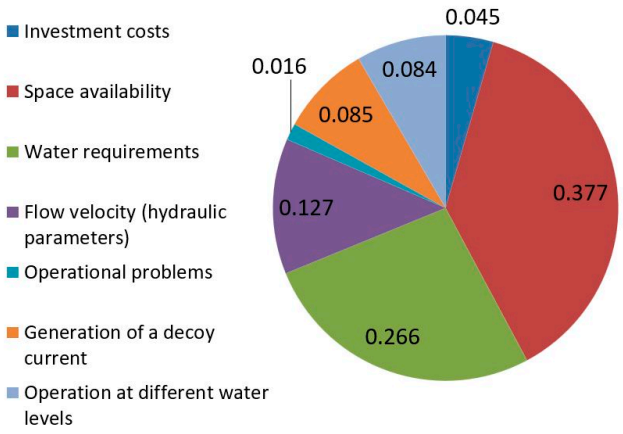


Figure 5. Summary of vector results of solution for level II of the hierarchical tree solved using the Rembrandt method.

Based on the conducted study, it was found that one of the most important factors was the availability of space (0.377). The second most important factor is water requirements (0.266) and the third is adequate water flow velocity (0.127). Figure 6 shows the global vector values for level III of the hierarchical tree.

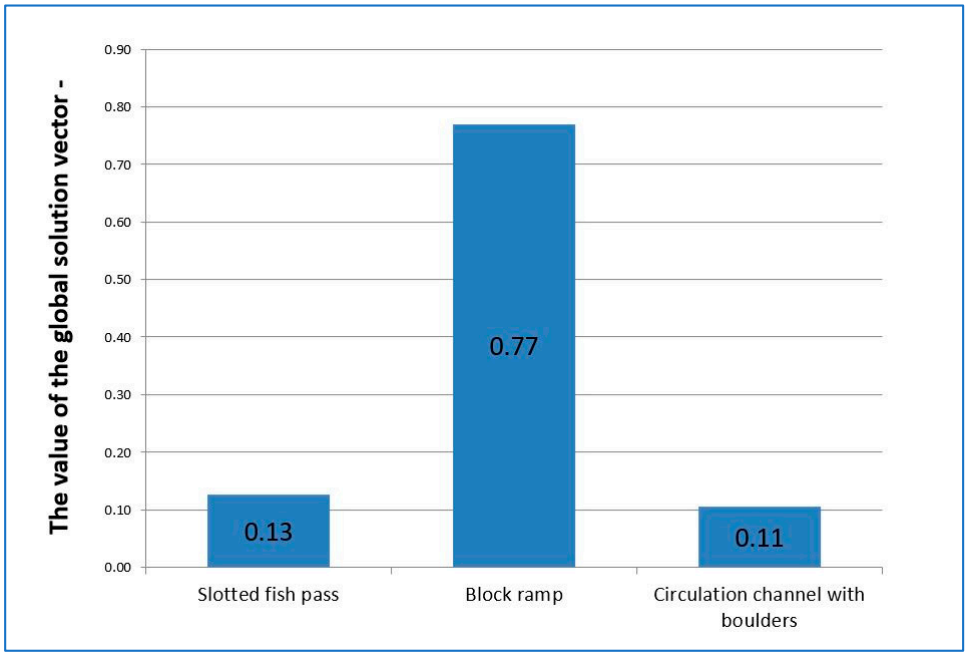


Figure 6. Summary of vector results of solution for level III of the hierarchical tree using the Rembrandt method.

Based on the analysis of the value of the third level global vector, it can be concluded that the most favourable solution is the construction of a block ramp (0.77), while the other

two types (a slotted fish pass and a circulation channel with boulders) obtained preference values of around 0.10.

Figure 7 shows the results of the level II matrix solution vector obtained using the AHP method. Similarly to the Rembrandt method, when the AHP method was used, the most important factor was space availability (0.330). The second most important factor was water requirements (0.277) and the least important was operational problems (0.024). Figure 8 shows the results of calculations of level III of the hierarchical tree, carried out in accordance with the assumptions of the AHP method.

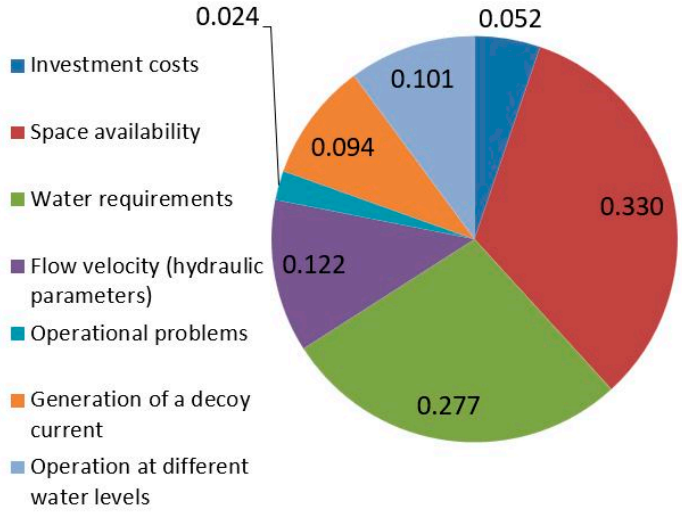


Figure 7. Summary of vector results of solution for level II of the hierarchical tree solved using the AHP method.

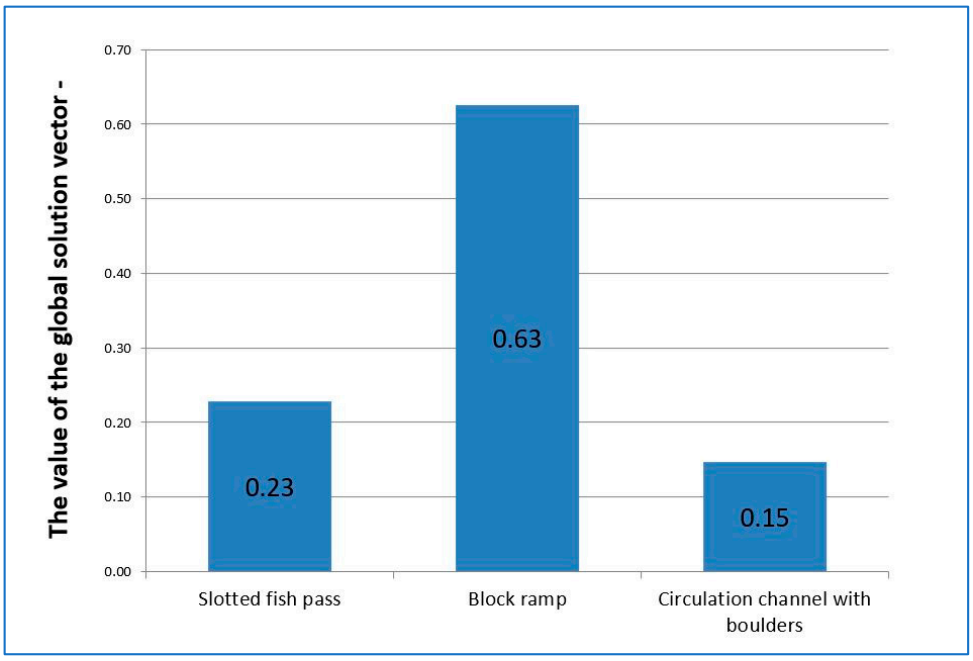


Figure 8. Summary of vector results of solution for level III of the hierarchical tree using the AHP method.

The global vector of the solution, in accordance with the assumptions of the AHP method, indicated that the most favourable option is to build fish passes in the form of a block ramp (0.63). The values of the global vector were at a similar level for the slotted fish pass and circulation channel with boulders and amounted to 0.15 and 0.23, respectively.

The results obtained using the two multi-criteria decision analysis methods are similar at every level of the hierarchical tree. The largest differences for level II relate to the availability of space in the fish pass that is favourable to fish and amounted to 0.05. The remaining factors at level II differ from each other by 0.01 or are equivalent for both calculation methods. Table 2 compares the global vector results for level III of the hierarchical tree depending on the calculation method.

Table 2. Summary of global vector results for level III of the hierarchical tree.

Type of Fish Pass	Multi-Criteria Decision Analysis Method	
	AHP	Rembrandt
Slotted fish pass	0.23	0.13
Circulation channel with boulders	0.15	0.11
Block ramp for fish	0.63	0.58

At level III of the hierarchical tree, the largest difference was recorded for the slotted fish pass and was 0.10. For the remaining solutions, i.e., the block ramps and the circulation channel with boulders, the difference between the values of the global vector calculated using the Rembrandt and AHP methods were 0.05 and 0.04, respectively. On the basis of the analyses carried out, it can be concluded that the greatest differences were observed between the results of the individual methods at level III of the hierarchical tree. However, they had no significance when selecting the type of fish pass solution.

When selecting a particular type of fish pass, the factors indicated at level II of the hierarchical tree provide the answer that the most important were the availability of space and the water requirements. Based on the results summarised in Table 2, it can be concluded that the differences in the methodology of the multi-criteria decision analysis methods used, which consisted of a different way of assigning weights when comparing factors and solutions, as well as changes in the way the matrix was recalculated, did not have a significant impact on the results obtained, especially in terms of the selection of fish pass type. It is significant that both the AHP method and the Rembrandt method indicated that the best solution for a fish pass on mountain rivers is the use of a block ramp.

The value of 0.7700 obtained for the block ramp using the AHP method suggests greater variability in this method. Method 1 has a more even and concentrated distribution, with higher results in the lower and middle parts of the range, and its results are less variable. Method 2 shows a wider spread of results, with significantly lower values in the lower part, but higher values in the upper part of the distribution, suggesting greater variability and the presence of extreme values. To compare both methods, a Bland–Altman plot was used (Figure 9).

The average difference between the two methods is approximately −0.00083. This is close to zero, which suggests that the measurements from both methods are generally consistent, with a slight tendency for the results from Method 1 to be somewhat lower. This means that the results obtained from the AHP method are slightly lower than those from the Rembrandt method. The standard deviation of the difference is about 0.1497, indicating moderate variability in the differences between the measurements from both methods. Most of the points lie within acceptable limits, which suggests that the differences between the methods are acceptable in most cases. Only one point is near the boundary, which may indicate that, in some cases, the results from one method significantly differ from the other. The Bland–Altman plot indicates that both methods yield similar results, with a tendency for Method 1 to provide slightly lower values compared to Method 2. The values are generally consistent, and the distribution of differences is relatively stable, making these methods useful for measurements in the context of the analysed data. Although the averages are almost identical, Method 2 shows a wider range of results, which may be important when selecting the appropriate method depending on the context of use.

The differences between the systems relate to their procedural operations. First, Rembrandt replaces the ratio scale suggested by Saaty with two longer scales. The second procedural difference was in the calculation of impact scores. Use of the geometric mean in the AHP analysis yielded a different recommended solution than use of the arithmetic mean. The ranks of the first two alternatives were, in fact, reversed. As might be expected in cases when the ranks are reversed, the scores for the reversed alternatives were very close with both methods. The Rembrandt system yielded the same rank order as AHP with the geometric calculation of impact scores. There was a slightly more divergent scoring of the alternatives, which can be explained by the use of longer scales. The third procedural difference lies in how alternative scores are aggregated for the criteria. While this also may have had some impact on the greater divergence of the scores between Rembrandt and AHP, the relative impact seems to be minor.

In summary, the similar results of the two methods are due to their common evaluation logic, hierarchical structure, and pairwise comparisons, and the differences in the way weights were assigned were not significant enough to change the final choice [46].

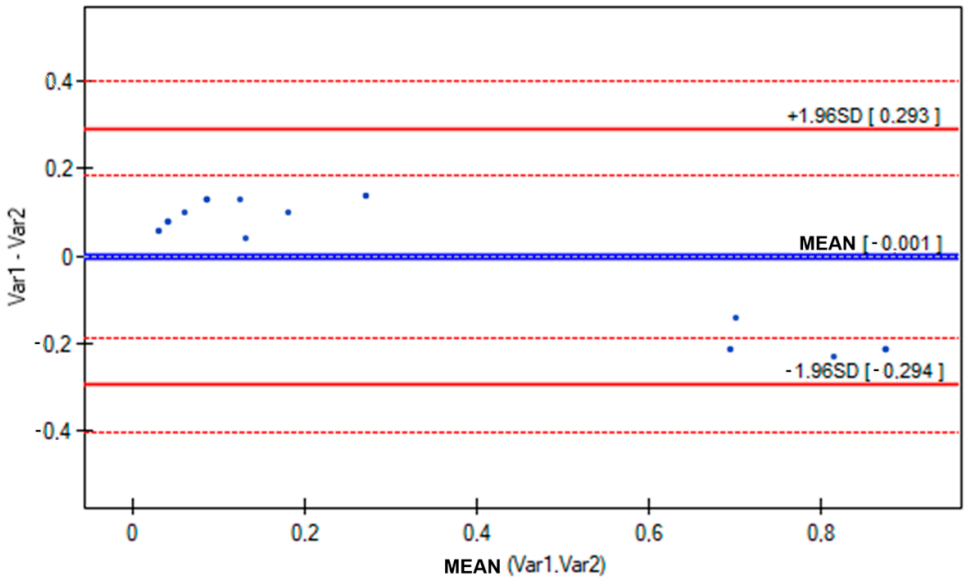


Figure 9. Bland–Altman plot results for data from the compared AHP and Rembrandt methods (mean difference—dashed blue line; boundary lines—red line).

4. Discussion

4.1. The Sensitivity Analysis

The sensitivity analysis involves examining how changes in the weights of the criteria used, such as space availability, water demand, and water flow rate, affect the final result. The sensitivity analysis was performed by systematically adjusting the weights assigned to these factors in both the AHP and Rembrandt methods, which allowed us to determine whether the preferred solution—the rapids design—remains the best solution under different conditions. The steps for implementing this analysis included, among others, determining the scenarios of the adopted weights. The weight values were developed with values of +1 and −1 relative to the adopted original values. The global vectors were recalculated. Both the AHP and Rembrandt methods were rerun using the new weight values, and the global vectors of the solutions (rapids, slot fish pass, and boulder circulation channel) were compared in these scenarios.

The impact of the introduced changes was analysed (Figure 10). A stable result was determined—rapids still received the highest score. This confirms the adoption of the correct weight values, which, despite the adoption of some minor "disturbances", do not ultimately affect the obtained solution. Similar conclusions were obtained in [47],

indicating the stability of multi-criteria methods within the framework of the correctly adopted recognition of the research problem.

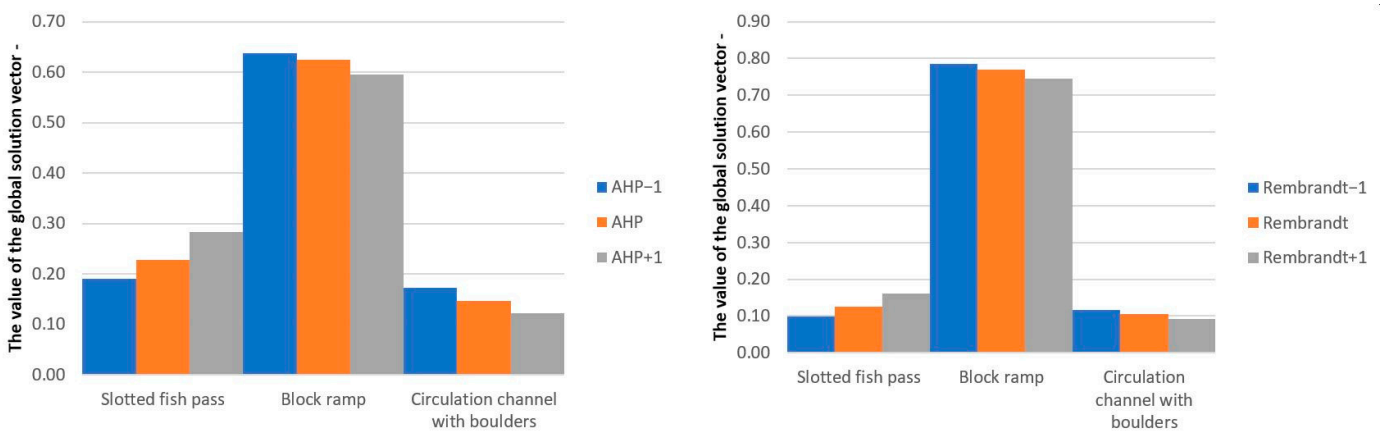


Figure 10. Sensitivity analysis for AHP and Rembrandt methods.

4.2. The Problem of Selecting the Optimal Type of Fish Pass

When assessing the different cost categories of fish passes under different electricity price scenarios, construction (45–87%) accounts for the largest share compared to operation (0–1.2%) and power losses (11–54%) [48]. Wolter and Schomaker [49] stated that the main objective here was deriving general guidance for the minimum amount of water needed for a fully functioning upstream fish passage in relation to river size. There was a significant correlation between the functionality and design discharge of a fish pass.

Čubanová [50] recommend that it is essential to carry out field measurements on constructed fish passes, which should be correlated with ichthyological studies in order to ensure that the migration efficiency of water structures is as high as possible. When analysing the hydraulic conditions in a nature-like fish pass, the authors found that assessing an existing fish pass according to theoretical recommendations is a long process. It requires a large amount of data and the involvement of experts from various fields. A study of the fish pass on the Wisłok River carried out by Kubrak [51] using the described engineering method is based on an assumed minimum specific energy concept in the individual fish pass sections. On the basis of the study, the authors found that, at the lowest flows, the water depth in the fish pass is too small and amounts to 0.46 m, which does not meet the minimum requirements (0.8–1.0 m).

In order to improve the effectiveness of fish passes, more and more new solutions and elements are being taken into account. Kucukali and Hassinger [52] found, based on studies on a physical model, that adding brush elements in the form of bristles to a slotted fish pass has a beneficial effect on energy dissipation by 17% in the chambers, reducing the velocity by 20%. Turbulent flow and areas of recirculation disappeared and slowdown zones decreased after the installation of brush blocks in the pool. Another interesting solution is the use of meander fish passes [53,54]. The literature suggests that it is essential to conduct continuous testing of hydraulic flow conditions to verify the proper functioning of passages and make any feasible adjustments to their geometry. A very important problem is how to provide the fish with an appropriate attracting water stream. Li [55] found, on the basis of a study on the Jinsha River, that the addition of an additional wall between the hydropower plant and the fish pass, as well as raising the bottom level, result in an enhancement of the attracting water stream [56].

4.3. Operating Conditions for the Block Ramps

As the analyses showed, the best solution to ensure the effective, two-way migration of fish is the use of block ramps (Figure 11a). These are structures that meet technical and engineering requirements, but also successfully perform ecological tasks [40,57]. These

structures are often arranged in a way that causes the stream to concentrate in the central part of the structure (Figure 11b) [58]. Moreover, they should have an appropriate slope so as not to interfere with the migration of aquatic fauna. At the same time, they serve as bed stabilisation below, e.g., bridges or culverts, they serve as elements of protection against channel erosion, they reduce the slope of the watercourse, and they lead to the restoration of channel beds [59–61]. These structures can successfully replace traditional vertical concrete barrages [62].

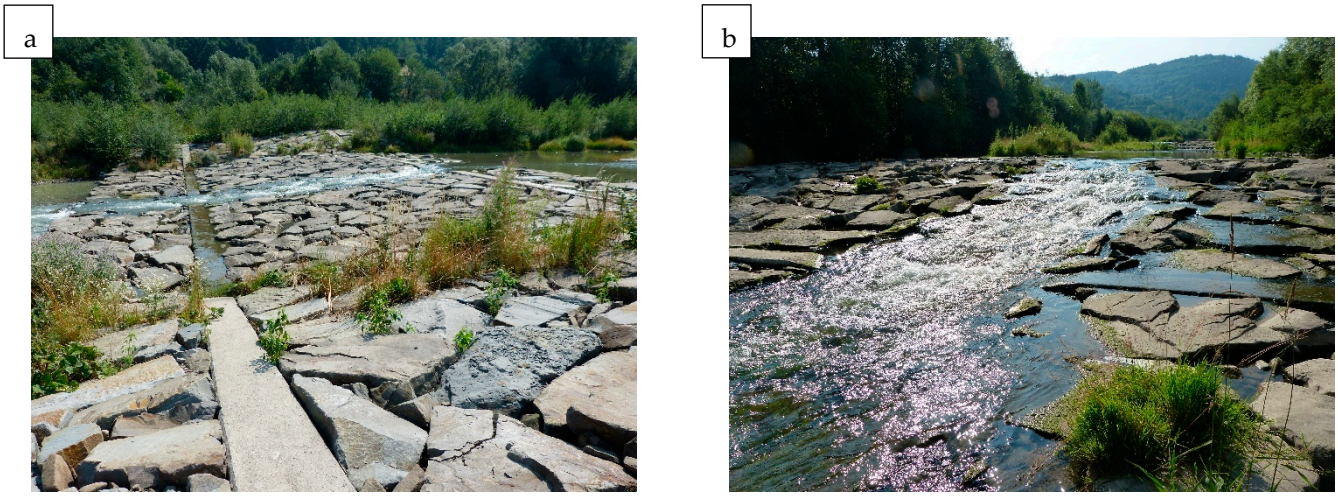


Figure 11. (**a**) Block ramps on the Porębianka stream and (**b**) depression-concentrating water streams on the slope apron of the block ramps.

Their construction in the field should be supported by analysis and numerical modelling, as if they are not built correctly, there may be reveal deficiencies in their design [63,64]. The main problems related to their improper construction include too high an inclination of the slope apron, the instability of the stones building the slope apron, and too high a flow velocity in the depression, concentrating the flow [58]. All of these deficiencies may prevent or significantly impede fish migration through the structure [65]. Improving the design of block ramps should mainly consist of reducing the flow rate of water that flows over them. The easiest way to do this is to reduce the inclination of the slope plate. However, this entails inevitable further consequences in the form of the lengthening of the facility, which results in the need to increase the length of the riverbed. Therefore, a "golden mean" should be found—the optimal inclination of the slope plate, which will not be too steep (then, too-high flow rates dominate and the stability of the stones that build the slope plate is reduced) and will not be too flat (then, it is extended, which results in its excessive length and increased construction costs).

These structures harmonise aesthetically with the landscape, especially in the channels of Carpathian rivers where gravel and stone sediment dominate. Although they can be used in the channels of sand rivers, there is then the danger of sanding the block ramps, which would significantly impair the dissipation of the kinetic energy of the flowing water and the efficiency of fish migration. In such cases, it is recommended to install a sediment trap in front of the block ramp to catch excess transported sediments [60,66].

Block ramps also create better biological conditions in the stream through the increased oxygenation of the water for macrobenthos and fish, and harmonise well with the landscape [67,68]. Block ramps can serve as tools for the revitalisation (restoration and stabilisation) of the river system. The restoration of the ecological balance of the watercourse must go hand in hand with a thorough understanding of the problems associated with restoring and repairing the degraded ecosystem. A degraded stream is defined as a stream where biological potential is lacking and the hydrological regime is significantly changed. The revitalisation of the aquatic ecosystem can be understood as technical and biological activities aimed at improving the inappropriate abiotic structure in the technical

regulation of the stream. The revitalisation measures focus not only on the aquatic but also on the coastal sphere, with the aim of achieving the optimal biodiversity of flora and fauna and a state of dynamic equilibrium in the stream. Hence, revitalisation involves restoring or improving the quality of the natural functions of the stream, which, as a linear and creative landscape element, is of great importance in the ecosystem. In turn, the concept of renaturalisation can be seen as the restoration of a stream so rigorous that it leads to the return of the original ecosystem in a natural state, with its original biodiversity and the ability to self-regulate [69–72].

Block ramps, if properly constructed, are less troublesome to operate than classic technical fish passes, which often fail to perform their function. The biggest problems with fish passes are the lack of an attracting water stream, chambers filled with sediment, the clogging of slots and overflow windows with wood debris, and sensitivity to changing water table levels in the channel (Figure 11). These phenomena do not normally occur on the slope apron of block ramps.

The attracting water stream is a kind of indicator for fish, showing the entrance to the fish pass. Its effectiveness in guiding fish depends on the hydrological conditions, which vary throughout the year. Often, it may not be present, which makes it difficult for fish to enter the fish pass. There is no problem regarding the presence of attracting water streams on block ramps as structures partition the river channel along its entire width. Migrating fish will eventually find their way to the structure. The only problem may be choosing the appropriate migration route between the rocks of the block ramps, but the varied design of the structures and the multitude of slots/pools should not constitute a block (after all, if not this route, another one will be found and swum through). This has been confirmed, among others, by research on Carpathian rivers [65]. The problem of a lack of attracting water stream often results from irregularities in the construction of the structure. However, this adverse effect can be enhanced by unfavourable hydrological conditions. High and even medium water levels in the river channel may disturb the attracting water stream flowing from the fish pass. On the other hand, low water levels may also be unfavourable, as the water stream flowing into the fish passes may have too low a flow velocity to generate such a water stream.

Sediment carried in during flood events is often retained in the fish pass chambers, preventing the pass from functioning effectively. This phenomenon also occurs on the slope apron of block ramps, although it can take two forms depending on the type of structure. In the case of block ramps with an erratic slope apron, coarse sediment can be deposited in the slots, while fine sediment is thrown down. On the other hand, on the cascading slope apron of the block ramps, there can be, as in the case of technical fish passes, backfilling of the bottom of the pools. In both cases, the monitoring of structures after flood events is necessary, although cascade-type block ramps are more vulnerable to this phenomenon.

Woody debris is usually thrown through block ramps. Only on structures with very low slopes of the slope apron is it possible to see tree roots, logs and trunks deposited on them. Even in such a situation, this does not constitute a migration block for fish. The sediment usually rests on the rocks, without obscuring the slots through which the fish migrate. On the other hand, sediment (but also rubbish of anthropogenic origin) entering a classic (e.g., slotted or chamber) fish pass clogs the holes and slots. This clogging blocks the migration route of ichthyofauna, as there is usually no possibility for the fish to find another crossing, as in the case of block ramps. Therefore, this operational aspect of the studied fish passes, as described above, also had to be taken into account when selecting the optimal solution.

Figure 12 shows only some of the problems encountered in Carpathian fish passes. In Figure 12a, the chambers of the semi-natural fish pass are not filled with water. This lack is due to the incorrectly designed inlet to the fish pass; when the water level is low, the water stream does not flow into the structure [38]. This is because the bottom of the inlet chamber to the fish pass is too high in relation to the low water level in the riverbed. The bottom cuts off the water flow to the fish pass. A similar situation can be seen in Figure 12b,

where the water stream also does not flow into the fish pass, but the reason for this is the silting of the channel at the entrance to the structure. The bar created there effectively cut off the water inflow to the fish pass. It should be noted that a similar situation occurs at the outlet of the fish pass—silt deposits are also observed. The chambers of the fish pass, which were silted up when the water flow was still entering the structure, consequently caused vegetation growth when there was no water inflow later. The chambers were silted up due to the large amount of fine sediment supplied to the fish pass. The accumulation of this sediment was caused by the too-low flow velocity through the fish pass chambers—the required non-silting velocity was not achieved. In Figure 12c, the technical condition of the fish pass is critical. There are visible defects in the concrete. The chambers are silted up and the overflow windows are partially clogged. There is little water in the chambers because little water flows into the fish pass, which is caused by the partial clogging of the inlet and the shallowing of the chambers. The chambers should be desilted and cleaned. You can see the lack of fish pass monitoring. In Figure 12d, there is an observed lack of an attracting water stream at the outlet of the fish pass. The outlet is clogged with a mixture of river sediment and wood debris, effectively reducing the speed of water flowing out of the fish pass, and thus eliminating the attractant current. In this case, the fish cannot find the entrance to the fish pass. They cannot enter the fish pass through the clogged hole even if they accidentally find it. To resolve the problems described above, this facility should be monitored and cleared by removing the debris.



Figure 12. Examples of a lack of functionality in fish passes. (**a**) the semi-natural fish pass without water (**b**,**c**) pool/chamber fish passes in critical technical condition (**d**) no attractant current in the outlet of the fish pass.

The problem analysed in the paper is extensive and interdisciplinary. Due to editorial limitations, it is difficult to include all the data in the paper, including those obtained by other researchers, hence the frequent references to and citations of other publications to create a body of knowledge.

The modification of fish passes should consist of a layout of the elements of the object (especially pools and spillways/slots) such that a continuous flow of water is ensured in hydraulic conditions that are optimal for the species of fish observed in the riverbed. Fish passes are often designed and constructed according to engineering principles using guidelines that specify the necessary geometric dimensions of individual elements. Unfortunately, this does not always ensure the success of the object. The biggest problem in current fish passes is the variable, often extreme (drought, flash flood) hydrological conditions, which create hydrodynamic conditions outside the norm. A solution could be monitoring the fish passes and controlling the inlet gates, limiting the impact of excess water. A balance reservoir could also eliminate, to some extent, the problem of water levels in the fish pass that are too low.

Our work is not a document containing only raw data. On the basis of properly processed data, our goal was to test the possibility of using multi-criteria decision support methods for a specific case, namely the selection of the optimal type of fish pass. Hence, you can also consider our work as an inspiration and a contribution to further research.

5. Conclusions

The selection of the most favourable type of fish pass is not simple, especially if the needs of all users and the manager of the water structure are to be taken into account. It is therefore worth using multi-criteria decision analysis methods when designing fish passes. Such methods allow for a broader look at the analysed problem and are particularly helpful in modern river engineering.

In a comparative analysis of the Rembrandt and AHP methods, the key factors influencing the effectiveness of fish passes at hierarchical levels II and III were examined. The results of both methods indicated that the availability of space and water requirements were the most important factors in the design of the fish passes. The availability of space received the highest weight (0.38 according to the Rembrandt; 0.33 according to the AHP) and water requirements was the second most important (0.27 for the Rembrandt; 0.28 for the AHP). The water flow velocity, although significant, was of lesser importance (0.15). At level III of the hierarchical tree, both methods indicated that the most optimal solution was the construction of a riffle, which received a significant advantage in the rating (0.77 for the Rembrandt and 0.63 for the AHP). The slotted fish passes and circulation channel with boulders received significantly lower preference values. The results of both methods were similar, and the differences between them, although noticeable (e.g., 0.10 for a slotted fish pass), did not influence the final selection of the most favourable solution.

The discussion showed that conventional fish passes are less effective compared to semi-natural solutions, which simulate natural river conditions using materials such as rocks and stones. Natural fish passes are more universal and friendly to various fish species, especially in cases with obstacles of low or medium height. For effective fish migration, it is necessary to ensure that there is a minimum amount of water in the fish pass, which is strongly correlated with its functionality. The studies indicate the need for regular field measurements and adjustments to the geometry of the fish ladders to improve their effectiveness.

In the context of engineering solutions, block ramps are considered the most effective, both in technical and ecological terms. However, accurate numerical modelling is required in their construction to avoid design problems that may affect the efficiency of fish migration. Compared to traditional fish passes, the riffles offer better biological and aesthetic conditions, harmonising well with the natural landscape. An important condition for the environmental effectiveness of a fish pass is the consideration of changing hydrological

conditions, regular monitoring of its technical condition, and the adaptation of the structure to the specificity of local water ecosystems.

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