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AN INTEGRATED KPI-BASED FRAMEWORK FOR THE EVALUATION AND CLASSIFICATION OF NATURE-LIKE FISH PASSES – A CASE STUDY OF THE FREUDENAU HYDROPOWER PLANT

Abstract:

Nature-like fish passes are complex hydraulic–ecological systems whose performance is often assessed through fragmented monitoring approaches. This paper proposes an integrated KPI-based framework for the evaluation and classification of fish pass functionality, combining biological, hydraulic, and operational indicators within a structured methodology supported by defined thresholds. A segment-based analytical approach enables classification as fully functional, selectively functional, or insufficiently functional. The framework is applied to the Freudenau fish pass (Danube River, Vienna), demonstrating how hydraulic and operational data can be integrated into a transparent and reproducible evaluation model for regulatory verification and long-term management.

Keywords: Nature-like fish pass; KPI evaluation; Fish monitoring; Functional classification

UИНТЕГРИСАНИ ОКВИР ЗАСНОВАН НА KPI ЗА ЕВАЛУАЦИЈУ И КЛАСИФИКАЦИЈУ CLOSE-TO-NATURE РИБЉИХ СТАЗА – СТУДИЈА СЛУЧАЈА ХЕ FREUDENAU

Сажетак:

Природни типови рибљих стаза представљају сложене хидраулично–еколошке системе чија се функционалност често процењује кроз фрагментисане приступе мониторингу. У раду се предлаже интегрисани методолошки оквир заснован на кључним показатељима перформанси (KPI) за евалуацију и класификацију функционалности рибљих стаза, који комбинује биолошке, хидрауличке и оперативне индикаторе у оквиру структурисане методологије подржане дефинисаним праговима прихватљивости. Сегментно заснован аналитички приступ омогућава класификацију система као потпуно функционалног, селективно функционалног или недовољно функционалног. Оквир је примењен на обилазницу рибље стазе Freudenau (Дунав, Беч), при чему је приказано како се хидраулички и оперативни подаци могу интегрисати у транспарентан и поновљив модел евалуације за потребе регулаторне верификације и дугорочног управљања системом.

Кључне ријечи:рибља стаза природног типа, KPI евалуација, мониторинг риба, класификација функционалности

1. INTRODUCTION

Fish passes represent a key measure for restoring the longitudinal connectivity of watercourses disrupted by the construction of dams and hydropower facilities [1]. Although their implementation has become a legal obligation in many European countries in accordance with the European Union Water Framework Directive [2], particular challenges arise in the case of nature-like fish passes, whose hydraulic and morphological behaviour is highly variable and dependent on seasonal water level fluctuations, sediment dynamics, and vegetation development, as extensively documented in the literature [3].

Despite their widespread application, the functionality of fish passes is often assumed rather than systematically verified based on measurable performance indicators [4], [5]. In the absence of a clearly defined monitoring protocol, it is difficult to reliably determine whether a fish pass operates as fully functional, selectively functional, or significantly constrained for certain species and size classes [6].

Fish pass monitoring has a dual role: to demonstrate passage efficiency in accordance with ecological requirements and to provide operational data necessary for system maintenance and optimization. Modern automatic counting techniques and digital monitoring systems further expand the possibilities for system evaluation [7].

Numerous studies address individual aspects of fish pass monitoring—either through biological assessment of passage success or through hydraulic analyses. However, integrated approaches that combine biological, hydraulic, and operational indicators into a unified, quantified, and classification-based model of functionality remain insufficiently developed, while acceptance thresholds are not consistently defined in regulatory practice.

The objective of this paper is to develop an integrated KPI-based methodological framework that enables a quantified, transparent, and reproducible evaluation and classification of fish pass functionality under real hydraulic and operational conditions, using a segment-based analytical approach.

2. OBJECTIVES OF FISH PASS MONITORING AND REQUIREMENTS FOR FUNCTIONAL VERIFICATION

Fish pass monitoring represents an integral component of water infrastructure management from the perspective of maintaining ecological continuity. Its purpose extends beyond the mere recording of fish presence and includes the demonstration of system functionality under real hydraulic and operational conditions.

From an engineering standpoint, fish pass monitoring serves three primary objectives:

1) Verification of passage efficiency – confirming that the system enables fish migration in accordance with the design parameters and target species requirements;
2) Control of hydraulic conditions – monitoring the stability of flow velocities, water depths, and discharge regimes during dominant migration periods;
3) Operational sustainability – identifying morphological changes, sedimentation processes, and variations in water supply regimes that may affect long-term system performance.

In nature-like systems, such as the fish pass at the Freudenau hydropower plant, functionality is particularly sensitive to discharge variability, seasonal water level fluctuations, and morphological transformations of the channel. Therefore, monitoring should not be considered a post-construction control measure, but rather an element integrated into the design phase and included in the technical documentation of the facility. In a regulatory context, monitoring provides:

- documentation required for technical acceptance,
- a basis for permits and certification procedures,
- support for operational revision and optimization,
- records of maintenance interventions.

A specific methodological challenge lies in the assessment of selective functionality, i.e., situations in which the system enables passage only for certain size classes or species or operates effectively only under limited hydraulic conditions. While complete system failure is relatively straightforward to detect, the identification of partial or conditional functionality requires the integration of biological and hydraulic indicators within a structured evaluation model.

For this reason, monitoring must be based on measurable performance indicators (KPI), enabling quantitative assessment and classification of system status, which forms the basis for the methodological framework presented in the following section.

3. METHODOLOGICAL FRAMEWORK FOR EVALUATION

The functionality of a fish pass cannot be assessed on the basis of a single indicator, but requires an integrated approach that encompasses biological, hydraulic, and operational parameters. In this context, the paper proposes a methodological framework based on a system of Key Performance Indicators (KPI), enabling quantitative and comparable system evaluation under different hydraulic and operational conditions.
The proposed framework is founded on the following principles:

- integration of biological and engineering criteria;
- use of measurable and repeatable indicators;
- ability to classify system functionality;
- applicability during design, technical acceptance, and operational phases.

3.1. STRUCTURE OF KEY PERFORMANCE INDICATORS (KPI)

The indicators are grouped into three primary categories:

- B – Biological indicators, referring to direct assessment of fish passage efficiency,
- H – Hydraulic indicators, characterizing flow conditions and morphological parameters relevant to migration,
- O – Operational indicators, encompassing maintenance factors, sedimentation processes, and continuity of system operation.

Table 1 presents the proposed KPI system, including indicator descriptions, measurement methods, and their relevance for functional evaluation.

Table 1. Key Performance Indicators (KPI) for Fish Pass Monitoring

Code	Indicator	Description	Measurement Method	Relevance for Evaluation
B1	Number of entering individuals	Recorded number of fish at entrance	Traps / automatic counting	Basis for migration intensity assessment
B2	Passage efficiency (η)	Ratio of fish at exit to fish at entrance	Tagging / counting	Quantification of functionality
B3	Residence time	Average time of passage through the system	Video / tagging	Indicator of hydraulic obstacles
H1	Velocity range	Minimum and maximum velocities in critical zones	Hydrometric measurements	Assessment of passage conditions
H2	Water depth	Depths in transitions and pools	Cross-section surveys	Stability of navigable profile
H3	Flow regime stability	Variations in velocities and depths under different discharges	Long-term monitoring	Sensitivity to hydraulic variability
H4	Frequency of exceedance of design velocities	Number of days/year with exceedance	Data analysis	Risk of selective functionality
O1	Sedimentation	Thickness of deposits in pools	Field inspection	Impact on hydraulic performance
O2	Blockages and obstructions	Record of debris accumulation	Operational records	Operational stability
O3	Water supply interruptions	Number and duration of interruptions	Operational data	Functional continuity

Although Table 1 includes the full KPI inventory for comprehensive monitoring, the formal classification model is based on a reduced subset of core indicators (B2, H1, H2, H4, O1, O3). These indicators were selected because they are directly measurable, comparable across monitoring periods, and representative of overall system functionality.

The remaining indicators are retained as supporting diagnostic variables for interpreting system behavior and planning corrective measures.

3.2. EVALUATION LOGIC

The methodological evaluation procedure follows a sequential process including:

1. definition of monitoring objectives;
2. identification of relevant KPI;
3. selection of measurement methods;
4. data acquisition and processing;
5. analysis of results according to defined acceptance thresholds;
6. classification of system functionality;
7. definition of corrective operational measures.

The evaluation process can be conceptually represented by the following sequence:

Monitoring objectives → Definition of KPIs → Data collection → Evaluation (K) → Classification F(K). In this way, monitoring is transformed from a descriptive procedure into a structured and quantifiable decision-making process.

3.3. PRINCIPLE OF FUNCTIONAL CLASSIFICATION

Evaluation of a fish pass does not end with the analysis of individual indicators; rather, it requires their integration into a unified decision-making system. In this context, system functionality is classified into three levels:

- fully functional,
- selectively functional,
- insufficiently functional.

A system is considered fully functional when all biological, hydraulic, and operational indicators fall within the designed or defined acceptance thresholds (Level I).

A selectively functional system is characterized by local or occasional deviations of certain indicators (Level II), where migration is not completely prevented but may be limited for specific fish categories or under particular hydraulic conditions.

A system is considered insufficiently functional when one or more indicators reach Level III, indicating systematic exceedances, operational interruptions, or significant limitations in passage performance.

Each classification level is associated with a different operational response. A fully functional system requires routine monitoring and standard maintenance. A selectively functional system indicates the need for targeted corrective measures, such as sediment removal, vegetation control, local hydraulic adjustment, or additional verification in critical zones. An insufficiently functional system requires priority intervention, detailed reassessment, and, where necessary, redesign or operational restructuring.

To formalize the evaluation procedure, the system of indicators can be represented by a performance vector:

$$\mathrm{K} = (B_2, H_1, H_2, H_4, O_1, O_3) \tag{1}$$

where the individual components represent the defined biological, hydraulic, and operational indicators.

Based on the defined acceptance thresholds (Table 2), a classification function is introduced:

$$F(\mathrm{K}) = \begin{cases} \text{fully functional,} & \text{if all indicators are at Level I} \\ \text{selectively functional,} & \text{if at least one indicator is at Level II} \\ \text{insufficiently functional,} & \text{if at least one indicator is at Level III} \end{cases} \tag{2}$$

In this way, fish pass evaluation is translated into a clear, transparent, and reproducible decision-making procedure, enabling comparability of monitoring results across different facilities and operational periods.

The proposed threshold values are intended as operational decision thresholds for engineering evaluation rather than universal biological constants. They were defined based on a combination of literature review, engineering interpretation of hydraulic and operational criteria, and expert judgment. Accordingly, the thresholds should be understood as a transparent and adaptable basis for classification, subject to adjustment for site-specific ecological and hydraulic conditions.

Where percentage-based interpretation is used, a value of 100% denotes full compliance with the defined target or design criterion for the respective indicator during the relevant monitoring period. In practical terms, this does not imply an abstract optimum under all conditions, but rather full conformity with the evaluation objective defined for that parameter.

The numerical classification thresholds are defined in Table 2 and constitute an integral part of the proposed methodological framework.

Table 2. Proposed Classification Thresholds for Fish Pass Functionality

Indicator	Fully functional	Selectively functional	Insufficiently functional
B2 – Passage efficiency (η)	$\eta \geq 70\%$	$30\% \leq \eta < 70\%$	$\eta < 30\%$
H1 – Velocity range	Within design range	Local exceedances	Systematic exceedances
H2 – Water depths	Stable and within design limits	Occasional reductions	Frequent critical reductions
H4 – Exceedance of design velocities	<10% of migration period	10–30%	>30%
O1 – Sedimentation	<10 cm	10–20 cm	>20 cm
O3 – Water supply interruptions	No interruptions	Occasional interruptions	Frequent or prolonged interruptions

4. MONITORING METHODS AND SELECTION MATRIX

The effectiveness of fish pass monitoring does not depend solely on the definition of appropriate Key Performance Indicators (KPIs), but also significantly on the proper selection of measurement methods. In practice, various techniques are applied, differing in reliability, invasiveness, operational complexity, and applicability under specific hydraulic conditions.

The selection of a monitoring method must be aligned with:

- the objective of assessment (quantification of passage efficiency, behavioral analysis, hydraulic control),
- the type of fish pass (technical / nature-like),
- turbidity and lighting conditions,
- availability of technical and human resources,
- regulatory requirements.

In practice, a combination of direct and indirect methods is most commonly applied in order to reduce uncertainty and increase the reliability of results.

4.1. DIRECT METHODS FOR PASSAGE ASSESSMENT

Direct methods enable the registration of fish presence and movement within the system and include:

Fish traps. Allow precise counting and species identification but require physical intervention and may temporarily disrupt migration continuity.

Blocking method. Based on temporary closure of the passage to assess fish accumulation. This method is technically demanding and applied only in limited cases.

Tagging and recapture. Enables estimation of passage efficiency (η) but requires additional processing and logistical support.

Electrofishing. Used for assessing fish populations upstream and downstream but carries a risk of injury and requires special permits.

4.2. AUTOMATED AND NON-INVASIVE METHODS

With technological development, non-invasive methods are gaining importance:

Video monitoring. Enables continuous monitoring without interrupting migration but is sensitive to turbidity and lighting conditions.

Sensor systems and infrared counters. Provide automated passage detection with high temporal data resolution.

The advantage of these methods lies in continuous data acquisition and reduced operational intervention; however, reliability may decrease under high turbidity or debris presence.

4.3. HYDRAULIC AND OPERATIONAL METHODS

For evaluation of hydraulic and operational indicators, the following methods are applied:

- hydrometric measurements of velocity and depth,
- cross-sectional profiling,
- continuous discharge and water level monitoring,
- field control of sedimentation,
- maintenance intervention records.

These methods form the basis for evaluation of hydraulic (H) and operational (O) indicators and enable identification of seasonal and operational variations within the system.

4.4. METHOD SELECTION MATRIX

To systematize the selection process, monitoring methods can be compared according to the following criteria: accuracy of passage assessment, data reliability, level of non-invasiveness, operational complexity, and application limitations. The comparative analysis presented in Table 3 serves as a basis for selecting the optimal combination of monitoring methods in accordance with the monitoring objectives and the specific characteristics of the fish pass. The 1–5 scale is used as a semi-quantitative expert-based ranking derived from literature review and engineering judgment.

Table 3. Comparative Evaluation Matrix of Fish Passage Monitoring Techniques

Method	Direct assessment	Stock assessment	Non-invasive	Reliability	Complexity	Limitations
Fish traps	5	2	1	5	4	Flow interruption; handling required
Blocking	4	1	1	3	5	Technically demanding; clogging risk
Tagging/ recapture	5	4	3	5	4	Recapture and post-processing required
Electrofishing	1	5	1	3	3	Injury risk; permit required
Auto counting (video/sensors)	5	2	5	4*	2	Turbidity/ light sensitive

Note: Scale 1–5 (1 = low; 5 = high); * reliability may decrease under high turbidity or poor lighting.

4.5. INTEGRATED APPROACH

Practical experience shows that no single method provides a complete evaluation of fish pass performance. Therefore, an integrated approach is recommended, combining:

- biological methods (B indicators),
- hydraulic measurements (H indicators),
- operational records (O indicators).

Such a combination reduces uncertainty, enables identification of selective functionality, and supports reliable decision-making regarding corrective measures.

5. CASE STUDY: FISH PASS AT HPP FREUDENAU (VIENNA, AUSTRIA)

5.1. MAIN SYSTEM CHARACTERISTICS

The fish pass at HPP Freudenau is located on the left bank of the Danube River and connects the main river channel with the New Danube diversion channel, which also serves for flood conveyance. The system is of a nature-like type and forms a river island with associated biotopes. The total head difference between the reservoir level and the downstream water level under mean flow conditions is approximately 8.70 m.

The fish pass is of a combined type:

- the longer section consists of a bypass channel approximately 1000 m long, while
- the shorter section is constructed as a ramp along the banks and bottom, approximately 420 m long, with a series of pools.

To improve the technical interpretability of the case study, the longitudinal system representation was structured by characteristic sections and linked to monitoring-relevant hydraulic zones, while the aerial view is retained as complementary spatial context.

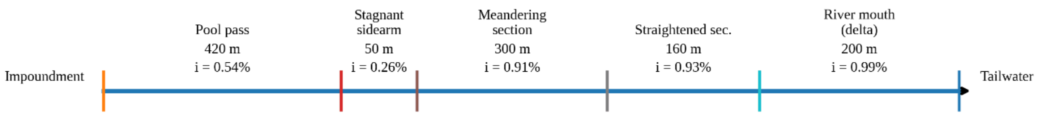

Figure 11. Longitudinal schematic of the Freudenau fish pass, segmented into characteristic sections with corresponding slopes and monitoring-relevant zones (created by author)

Figure 1. Aerial view of HPP Freudenau, showing the spatial relationship between the fish pass, the main Danube channel, and the "Neue Donau" diversion channel, provided as site context for the case study [9].

The entrance to the fish pass (water outlet) is designed in the form of a delta with three branches, two of which are permanently active, while the third is activated during elevated water levels. The entrance zone is located approximately 500 m downstream of the dam, ensuring hydraulic connectivity with the dominant flow field of the river within the immediate zone of influence of the structure.

5.2. WATER SUPPLY AND OPERATIONAL REGIMES

The fish pass is primarily supplied by overflow from the reservoir through the highest pool, at a discharge of approximately $Q \approx 900$ l/s. Under elevated mean water levels, the supply may decrease (due to hydraulic conditions and reservoir drawdown regimes), and additional supply is provided via a sluice gate at the dam (between the fifth pool and the reservoir). During high-flow conditions, the water allocated to the fish pass may be significantly reduced, and in certain situations temporarily suspended; in such cases, water retention in the system is maintained by a low-discharge pump, while fish passage is not enabled. During operation, a wide supply range is present, approximately 900–1500 l/s, with possible increases up to about 1800 l/s in certain periods. Additional supply to the bypass channel is provided through two pipes equipped with valves, adjusted according to season and water level. Operational significance of the supply regime: Flow variability directly affects velocity and depth distribution in key zones (entrance, transitions, meander section), as well as the occurrence of blockages and sedimentation. Therefore, the supply regime represents one of the primary hydraulic–operational monitoring indicators (H3, H4, O3). These data form the basis for evaluating indicators H3 and H4 within the proposed methodological model, as they allow quantification of the frequency and intensity of deviations from design hydraulic conditions.

5.3. HYDRAULIC CHARACTERISTICS AND CRITICAL ZONES

The hydraulic analysis was conducted according to the system segmentation shown in Figure 1, with individual sections considered as separate functional units. This approach enables direct linkage between the longitudinal geometry of the system and the defined hydraulic indicators (H1–H4), as well as identification of critical zones within the proposed evaluation framework.

5.3.1. Entrance Zone (Delta) and Initial Bypass Section

The entrance zone is the steepest part of the system (slope > 10%), characterized by pronounced geometric changes during high water levels, when delta flooding occurs and expanded, calmer zones are formed.

This zone is critical due to the combination of:

- changes in depth and width at high water levels,
- potential accumulation of sediment and floating debris, and
- alterations in the flow field depending on Danube water levels.

5.3.2. Bypass Channel – Straight and Meandering Sections

The bypass includes an initial straight reach, followed by a meandering section approximately 300 m long with slopes exceeding 10%, and then a section with lower slopes (up to about 3%) and channel widths reaching approximately 10 m. In the meandering section, higher slopes result in increased velocities and greater cross-sectional variability: reduced velocities near banks and increased velocities in rapids and outer bends. Hydrometric surveys indicate that, at discharges of approximately 1500–4000 l/s, clear hydraulic changes occur with increasing flow, while channel stability is maintained even during higher test discharges. In the meander section, velocities up to approximately 2 m/s may occur in rapids at higher discharges, while a significant portion of the cross-section remains below 1 m/s, indicating spatial flow heterogeneity. Critical KPIs: H1 (velocity range), H4 (seasonal variability), O2 (blockages), O1 (sedimentation in widened zones).

5.3.3. Island Section (Flow Division into Two Branches)

The island section has a milder slope (~3%) and flow division into two branches. It is characterized by lower maximum velocities (generally below 1 m/s even at higher discharges), with localized increases immediately downstream of transitions, where velocities may reach approximately 1.75 m/s at maximum supply conditions. Operationally, this zone is significant because lower slopes and velocities may favor fine sediment deposition and the formation of shallow areas, requiring periodic morphological control and maintenance.

5.3.4. Ramp Section (Pools)

The ramp section consists of approximately 19 pools of varying dimensions (typically 20–40 m in length), with an average head difference of about 11 cm between pools. Rough and asymmetrically placed blocks ($d \approx 30$–50 cm) increase flow diversity and create zones of lower velocity. In central ramp areas, velocities are generally below ~0.25 m/s, while in transition zones they increase to approximately ~0.75 m/s. The highest velocities occur immediately downstream of transitions and may locally reach approximately 1.5 m/s. Operational aspect: Due to relatively low velocities and increased roughness, sedimentation occurs in certain pools, with original gravel–sand bed material covered by fine sediment layers of approximately $d \approx 20$ cm. Vegetation (e.g., willows) contributes to bank stabilization but may increase hydraulic resistance and alter flow distribution. Cases of obstruction due to animal activity (e.g., beaver dams) have also been recorded, influencing local water levels and causing blockages. Critical KPIs: O1 (sedimentation), O2 (blockages), O3 (morphological stability), H2 (pool depths), H1 (local maximum velocities below transitions).

5.4. APPLICATION OF THE PROPOSED FRAMEWORK: KPI MAPPING TO THE FREUDENAU SYSTEM

Within the proposed methodological framework, the Freudenau system can be analyzed through three indicator groups:

- Hydraulic indicators: control of velocity and depth ranges in transition zones, meander section, and entrance; monitoring the influence of supply variation (900–4000 l/s) on spatial flow heterogeneity.
- Operational indicators: sedimentation in ramp pools, blockages at the entrance during high Danube water levels, vegetation control and debris removal; identification of reduced or interrupted supply periods during floods.
- Validation (biological) indicators: at this stage, considered as monitoring objectives, with method selection (automatic counting and/or tagging) subject to implementation depending on visibility and turbidity conditions.

Priority monitoring tasks for Freudenau include:

- continuous discharge and water level recording,
- periodic hydrometric profiling in critical zones (entrance, transitions, meander), and
- sedimentation monitoring and maintenance tracking in ramp pools.

For objective functionality assessment, a classification model based on KPI acceptability thresholds is proposed. Defined numerical criteria enable unambiguous classification as fully functional, selectively functional, or insufficiently functional. Final classification is determined according to the dominant level of compliance, with particular emphasis on biological indicators during the migration period. System segmentation allows section-based performance evaluation, overcoming limitations of a single global functionality assessment.

An illustrative application of the proposed framework to the Freudenau system is presented in Table 4, using the currently available hydraulic and operational evidence.

Table 4. Illustrative KPI-Based Assessment of the Freudenau Fish Pass

Indicator	Available evidence	Preliminary assessment	Status / Classification level
B2 – Passage efficiency (η)	No direct biological data available	Biological validation pending	Not yet validated
H1 – Velocity range	Local velocities up to ~2 m/s in rapids and transitions	Local exceedances	Selectively functional
H2 – Water depths	Generally acceptable depths; local reductions possible	Acceptable with local reductions	Selectively functional
H4 – Exceedance of design velocities	Higher exceedance risk under increased supply	Occasional exceedance risk	Selectively functional
O1 – Sedimentation	Sediment deposits up to ~20 cm in some pools	Maintenance-sensitive	Selectively functional
O3 – Water supply interruptions	Reduced or suspended supply during floods	Occasional interruptions	Selectively functional

Based on the currently available hydraulic and operational evidence, the Freudenau fish pass may be preliminarily classified as selectively functional. This preliminary classification reflects local hydraulic exceedances, sedimentation-sensitive zones, and occasional supply-related limitations, while direct biological verification remains pending. Final classification should therefore be confirmed by biological monitoring, particularly through assessment of passage efficiency during the relevant migration period.

6. DISCUSSION

The analysis of the Freudenau fish pass shows that in complex nature-like systems, functionality is strongly conditioned by water supply regimes and seasonal water level variations. Although geometric parameters comply with general fish passage design recommendations [1], nature-like systems are characterized by pronounced hydraulic heterogeneity and morphological variability [3], complicating assessment of actual effectiveness.

The results confirm that functionality of nature-like fish passes depends less on geometry alone and more on supply regime stability and operational management. Similar conclusions are reported in [4], emphasizing continuous hydraulic monitoring. Modern automatic counting systems further improve temporal and behavioral migration analysis [7].

Compared to approaches relying primarily on biological indicators [5], the proposed framework integrates hydraulic and operational parameters, enabling identification of selective functionality.

Operational factors such as sedimentation, vegetation development, and supply interruptions are equally significant as hydraulic parameters. Regulatory practice highlights the need for formalized protocols and periodic performance evaluation [8].

Although EU legislation mandates longitudinal connectivity [2], quantitative classification criteria remain insufficiently standardized. Reviews [6] demonstrate significant variability in evaluation approaches.

A limitation of this study is the absence of direct biological passage measurements; future research should include long-term migration datasets and threshold validation across different fish pass types.

7. CONCLUSION

Monitoring of fish passes is essential for verifying actual functionality and cannot be reduced to post-construction inspection. Particularly in nature-like systems, hydraulic and morphological variability requires integrated, long-term evaluation.

This study developed a KPI-based methodological framework including a method selection matrix and numerical classification model. The approach enables objective classification as fully functional, selectively functional, or insufficiently functional.

Application to HPP Freudenau demonstrates that water supply stability and operational control are as important as geometric design parameters. Identification of critical zones confirms the necessity of continuous hydraulic–operational monitoring for adaptive management.

The proposed model supports standardization of evaluation and certification procedures and contributes to improved reliability of measures ensuring longitudinal river connectivity.

The framework is not limited to the Freudenau system and is applicable to other fish pass types with threshold adaptation to local hydraulic and biological conditions.

SUSTAINABLE DEVELOPMENT GOALS

Sustainable Cities and Communities

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