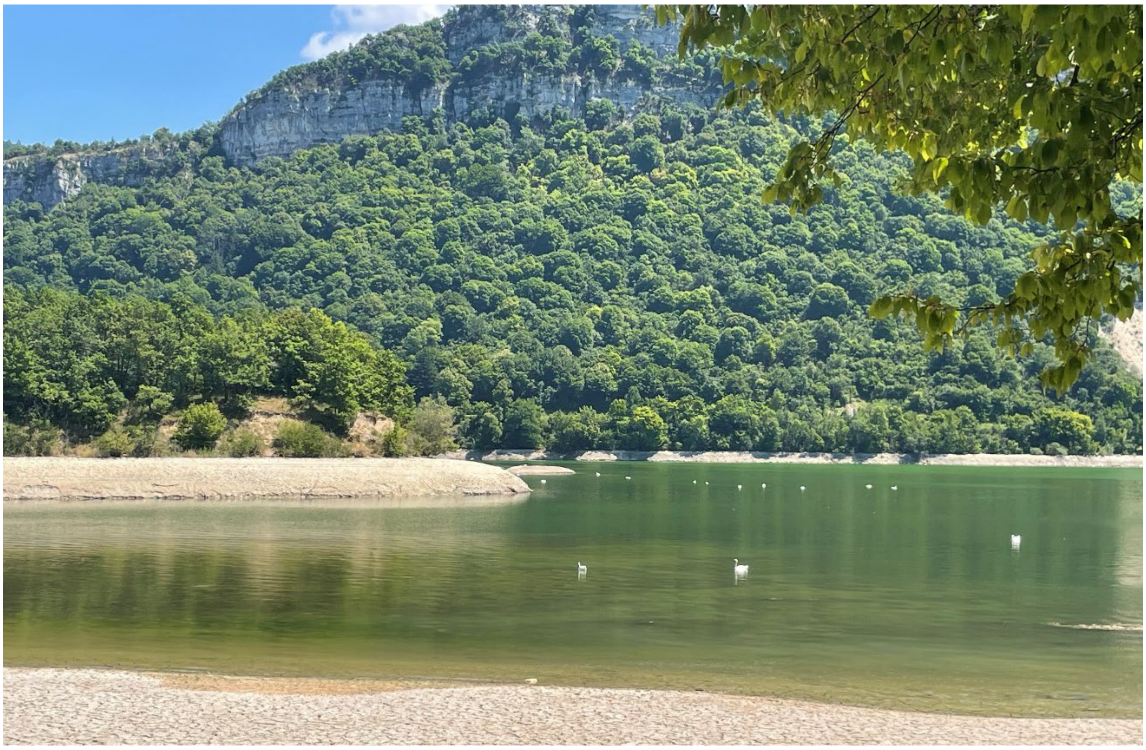
ReHydro

Demonstration of Sustainable Hydropower Refurbishment

D5.1 Hydropower pressures assessment: Framework for categorizing pressures and list of potential indicators



This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101147310

Deliverable No.	D5.1
Deliverable Title	Hydropower pressures assessment: Framework for categorizing pressures and list of potential indicators
Work Package Title	Societal Services
Dissemination level	Public (PU)
Due date	31.07.2025
Version	1
Status	Final
Submission date	08.08.2025

Contributors	Name	Partner	Date
Deliverable Leader	Agnès Barillier	EDF-CIH	23.07.2023
Work Package Leader	Julien Merlin	ENGIE	23.07.2023
Contribution Authors	Véronique Gouraud Leah Beche Stephane Descloux Ingebrigt Uglem Liliana Benites Carvalho Joana Santiago João Pádua Ricardo Branca	EDF-LNHE EDF-CIH EDF-CIH NINA EDP EDP EDPL EDPL	23.07.2023
Internal review	Mauro Carolli	SINTEF	08.07.2025
Final review and approval	Atle Harby	SINTEF	07.08.2025

DISCLAIMER / ACKNOWLEDGMENT

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Executive Summary

This deliverable, part of the ReHydro project funded by the European Union's Horizon Europe program, presents a comprehensive framework for assessing the environmental pressures exerted by hydropower projects, particularly in the context of refurbishment and modernization. The overarching goal is to support sustainable hydropower development that aligns with ecological and societal needs under climate change constraints.

Hydropower impacts on aquatic ecosystems are multifaceted and context-dependent, involving both local and global pressures. Traditionally, assessments have focused on local impacts during construction or operational phases, often neglecting the broader environmental footprint across the entire value chain. This report addresses that gap by proposing a dual-perspective approach—local and global—supported by a set of indicators to quantify pressures on biodiversity.

Key contributions of this deliverable include:

- **Categorization of Pressures**: The framework distinguishes between local pressures (e.g., river fragmentation, flow alteration, habitat degradation, water quality changes) and global pressures (e.g., greenhouse gas emissions, land use, water consumption, pollution from material extraction and transformation).
- **Indicator Development**: A detailed list of potential indicators is proposed to assess both local and global pressures. These indicators are designed to be applicable in early project stages using publicly available or easily obtainable data, facilitating eco-design and variant comparison.
- **Demonstration Sites**: Indicators will be tested on selected hydropower refurbishment sites (e.g., VSM, Rhône, Lima) to evaluate their feasibility, relevance, and ability to guide decision-making. The VSM site, involving significant construction work, will serve as a key testbed for validating the framework.
- **Future Perspectives**: The next steps involve refining and validating the indicators, ensuring their interoperability with existing sustainability frameworks (e.g., CSRD), and ultimately developing a biodiversity footprint index to support eco-design in future hydropower new or refurbishment projects.

List of acronyms

CF : Characterization Factor

CSRD : Corporate Sustainability Reporting Directive

EFHI : European Fish Hazard Index

GHG : Green House Gases

HCP : Habitat Change Potential

HPP : Hydropower plant

IHA : International Hydropower Association

LCA : Life Cycle Assessment

LCIA : Life Cycle Impact Assessment

LCTR : Long-term capacity ration

LIHI : Low Impact Hydropower Institute

LU : Land use

MQI : Morphological Quality Index

MSA : Mean species abundance

MVRS : Minimal Viable Range Size

PDF : Potentially Disappeared Fraction of Species

PSR : Pressure-State-Response

RCI : River Connectivity Index

VSM : Vouglans Saut-Mortier

WC : Water consumption

Glossary

Term	Definition
Anthropic pressure	Environmental pressure resulting from human activities, such as construction, pollution, or land use change.
Barrier effect	The impact of physical structures (e.g., dams, weirs) that hinder the movement of aquatic species and disrupt river connectivity.
Eco-design	A design approach that integrates environmental considerations throughout the life cycle of a project or product.
Ex ante assessment	An evaluation conducted before project implementation, based on estimates and available data.
Fragmentation	The division of rivers into disconnected segments, affecting ecological continuity and species migration.
Habitat suitability	The degree to which a specific environment meets the needs of living conditions for a particular species or community.
Hydropeaking	Rapid and frequent changes in river flow and water level caused by hydropower operations, often affecting aquatic habitats.
Indicator matrix	A structured tool that organizes indicators by pressure type to assess environmental impacts.
Lentic habitat	Still water environments with low water velocity such as pools, lakes or reservoirs, as opposed to flowing (lotic) systems.
Mitigation measures	Actions taken to reduce, improve or offset negative environmental impacts of a project.
Riparian zone	The interface between land and a river or stream, often rich in biodiversity and crucial for ecosystem health.
Sediment continuity	The natural transport of sediments along a river, which can be disrupted by dams, weirs and reservoirs.
Stranding	A phenomenon where aquatic organisms become trapped on dry land or in isolated pools due to sudden drops in water levels.
Thermal stratification	Layering of water in reservoirs based on temperature, which can affect oxygen levels and aquatic life.
Trophic state	A classification of the biological productivity of water bodies, indicating the total biomass present at a given time.
Upstream/downstream migration	The movement of aquatic species along a river, often obstructed by hydropower infrastructure.
Watershed	A land area where all precipitation drains to a common outlet, also called catchment.

1 Background

The main objective of ReHydro is to demonstrate how European hydropower systems can be refurbished and modernized to be fit for a leading role in the future power system respecting sustainability requirements and societal needs in a climate change context.

The pressures and impacts of hydroelectric power production on aquatic environments and freshwater biodiversity are highly context dependent. Their processes are generally well understood and assessed locally (He et al, 2025). Nevertheless, the entire value chain of a hydropower project (e.g. the use of machinery, extracted materials, energy sources used for construction) must be considered for a comprehensive assessment of pressures on ecosystems.

The assessment of the impacts of hydropower development is most often carried out either during construction or during the operational phase for modification works or concession renewals. It is based on local environmental characteristics and on *ex ante* risk analyses (supported by local environmental data and the operating characteristics of the development and feedback from experience). It leads to recommendations for measures to avoid or reduce local impacts on biodiversity, without considering the entire value chain and without quantifying their "global" (elsewhere on the planet) or on other components (increased carbon emissions) to ensure that these measures are truly 'no regrets' and that there will be no "transfer" of impact (by increasing another type of pressure, for example). It is therefore in the best interests of project developers to have a 'tool' that allows them to estimate how these pressures on biodiversity will evolve depending on the technical variants or impact reduction measures they are considering, considering the entire life cycle.

The ultimate objective of task 5.6 of the ReHydro project is to develop a tool for assessing the reduction in environmental impact achieved by renovating the structure, considering all impacts during the construction, operation and deconstruction phases. Depending on their nature, these modernizations may require works of varying scale, which will themselves have local but also global environmental impacts throughout the value chain. This is why we considered it necessary to develop tools that consider the 'burden' associated with these works against the benefits for biodiversity in the broadest sense.

To meet this objective, tools to design the "best" alternative (including the option of no project) considering local catchment impacts and scheme characteristics, other anthropic pressures, water uses, etc, and global impact based on life cycle impact assessment (LCIA), are needed.

To guide decisions, these tools must be used right from the start of the project development, with a systemic and global approach as much as possible. This can be rather challenging at this stage as technical or environmental data are not always available or are not accurate enough.

Moreover, LCIA approaches are not sufficiently developed to integrate aquatic biodiversity, especially those influenced by the presence or the operation of hydropower plants.

The objective of the present deliverable is 1) to identify and describe the pressures on aquatic biodiversity in "local" and "global" perspectives and 2) to identify potential indicators to quantify or assess these pressures. To this end, a bibliographic analysis of scientific literature was carried out. The next step will be to select indicators from this list of potential indicators, which will be tested at demonstration sites where major work is planned. This test will allow for an evaluation of their usefulness for analysing project variants within an LCA-compatible framework, as well as help guide changes to the indicators or thresholds or both.

2 Objectives

Literature on hydropower impacts is abundant (Quandt et al., 2022; He et al., 2025). This has improved the environmental impact assessment of hydropower project studies, but these assessments remain limited to local environmental and social impacts (on the rivers and riparian zones, water uses, …) that are directly concerned by the hydropower project, without considering impacts of the entire value chain.

On the other hand, hydropower LCA studies assess the hydropower pressure on the global environment, through quantification of energy and matter fluxes used to build and operate the scheme, but with limited consideration of biodiversity impacts. Hence, literature about quantification of anthropic pressures on aquatic biodiversity is rare or recent and incomplete, while the one related to terrestrial biodiversity is more developed.

Therefore, our objective is to provide a tool targeting local effects of HPP projects on biodiversity to complement the LCA, using a simplified quantitative or semi-quantitative approach.

The tool is intended to be complete regarding the hydropower pressures on environment. As it is designed to be used in the early stages of a refurbishment project as well as a new scheme, to help eco-design by comparing variants, it must be based on public or easily accessible environmental data.

3 Literature review

3.1 Local anthropic pressures on aquatic environment

3.1.1 General framework

In Europe, the European Water Framework Directive (2000) categorized the pressures exerted on aquatic environments that are likely to prevent them from achieving good ecological status.

The principles underlying this Directive are based on Pressure-State-Response (PSR) model initially developed in Canada in the 80s, which has been extended to the DPSIR (Driving forces, Pressures, State, Impact, Responses) model (EEA, 1999) (Stanners et al, 2009).

The pressure identified on watercourses are mainly pollutant discharges from human activities (macropollutants, nutrients, mineral or organic micropollutants), alterations to morphology (dams, weirs embankments, etc.) and alterations to hydrology (withdrawal, diversion, basin transfer, hydropeaking, etc.)

The metrics used mainly concern water quality, water quantity, biota and morphology.

- Pollution is assessed by searching for pollutants and comparing them to quality thresholds, using fairly standard approaches that are identical across different countries (EC, 2003).
- River hydro-morphological elements that are assessed refer to quantity and dynamics of water flow, connection to groundwater bodies, river continuity, river depth and width variations, structure and substrate of the riverbed and structure of the riparian zone (EC, 2003). In most European states, these hydro-morphological analyses required methodological development approaches that remained specific to each state (e.g. RCI, river connectivity index in Catalonia, Sola et al, 2014; or MQI, morphological quality index in Italy, Rinaldi et al, 2013, etc.)
- For biological communities, the various tools initially available to each country to characterize a particular aquatic biological community have been adapted to reflect 'deviations from the reference' specific to each type of watercourse. This concept of deviation from the reference for each type of watercourse makes it possible to compare the status of watercourses regardless of their type or the method used.

One of the limitations of the PSR model is its restricted spatial or thematic scope (Delavaud et al, 2021).

3.1.2 Hydropower pressures on rivers

Hydropower facilities constantly interact with upstream and downstream aquatic environments, as well as with adjacent riparian or terrestrial ones and local human societies. These effects vary in intensity, length, and surface area, and affect different compartments depending on the scheme, or the river or the territory characteristics. They therefore require a systemic and holistic view of their wide range of effects on all environmental and human components (Voegeli et al, 2019).

The nature of the local pressures of hydroelectricity production (or hydropower) on river functionality and aquatic biodiversity has been summarised in several bibliographic reviews (see, for example, Fengzy He et al, 2025). They are assessed using various indicators in the administrative approval processes for hydroelectric projects or in the certification processes for sustainable projects, such as those of the IHA (International Hydropower Association) or the LIHI (Low Impact Hydropower Institute).

Pracheil et al. (2019) compiled a checklist of indicators of river functioning influenced by hydropower, based on a review of the indicators used, which were consolidated into a database (EMH Database). The 51 indicators of river functionality were grouped into six categories: **biota, water quality, geomorphology, continuity, water quantity and land use** in the catchment area (Pracheil et al, 2019).

Going further, Voegeli et al. (2019) proposed, based on literature, cause-and-effect diagrams identifying the interactions and impacts of hydropower on different components of the environment, beyond the aquatic compartment. An example is given in Figure 1 relative to cause-to-effects relationships explaining the impacts on biodiversity and ecosystems. These diagrams consider the nature of the facility (large dam and reservoir, power plant, power lines) and environmental components (landscape, biodiversity, water quality, climate, natural hazards, socioeconomics, human health, societal acceptability, system services, and other services rendered). They thus reflect the complexity of these interactions and the difficulty of assessing the sustainability of hydroelectric projects as comprehensively as possible.

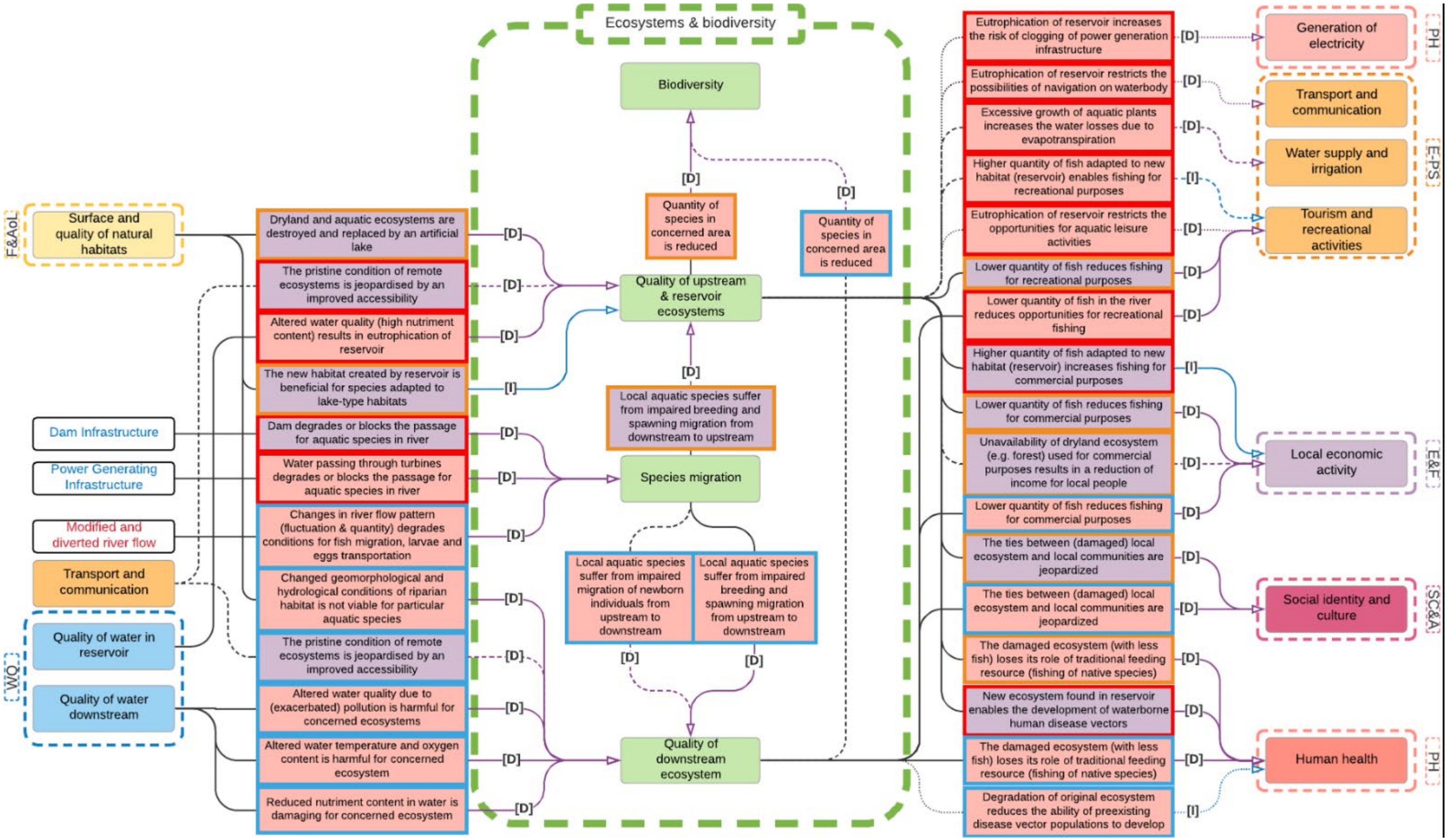

Figure 1. Example of cause-to-effects of hydropower pressures on ecosystems and biodiversity. From Voegeli et al, 2019 (Fig.7).

3.2 Global anthropic pressures on aquatic environment

3.2.1 General framework

3.2.1.1 Global pressures on biodiversity

IPBES grouped all anthropogenic impacts on global biodiversity into five categories of pressure, which are mainly related to changes in **land (or sea) use, climate change, pollution, overexploitation** of species and the introduction of **invasive alien species** (IPBES, 2019). Within this framework, we can identify different types of pressure on aquatic biodiversity:

- Land use: habitat or ecosystem destruction, fragmentation or perturbation (light, noise)
- Global change: thermal modifications, greenhouse gases (GHG), acidification, water regime modifications
- Pollutions: pollutants emissions
- Overexploitation: harvesting species beyond their stock renew
- Invasive alien species: may be introduced voluntary or not

In freshwater ecosystems at a global scale, IPBES estimates that the three main factors affecting the biodiversity are land use, pollution and direct exploitation, followed by climate change and invasive species.

3.2.1.2 LCIA framework

Within a global perspective, the main tool for assessing negative impacts on biodiversity in a comprehensive manner is based on the concept of Life Cycle Assessment (LCA) which has been standardized (ISO 14040, published in 1997, updated in 2006). In LCIA (**life cycle impact assessment)**, the inventory is analysed for environmental impact.

Its principle is to link 'flows' (emissions, consumption, activities) to different categories of pressures ('midpoints'), and these pressures to final environmental impacts ("endpoints"), via 'characterisation factors' from global databases, which are gradually enriched and updated as knowledge and models progresses. In LCA, characterization factors are numerical values used to convert and aggregate the environmental impacts of different items into common impact categories. All these assessments are reduced to a common reference (e.g. kg of resource used or kg of emissions) and the results are expressed in a unit of equivalence.

One of the strengths of LCA is its holistic approach, which is well suited to its objective of providing decision support for project developers and information for stakeholders. However, it is difficult to achieve the same level of accuracy for the different stages of the life cycle, and some impact models are still being developed for several categories of pressures (in particular water use, climate change, eutrophication or acidification, exotic species, resource exploitation) (Delavaux et al, 2021). The European Commission has therefore indicated the levels of reliability of the indicators used to assess the environmental performance of products over their life cycle (UC, Recommendation (UE) 2021/2279, 15/12/2021).

3.2.1.3 Which type of biodiversity is concerned?

A wide range of tools have been developed over the past 20 years, given their highly varied objectives of assessing the impacts of organisations as well as those of technological sectors, projects or products. As such, they do not share a common methodological framework (Fontanier et al, 2025) and result in a variety of reference units. For activities or projects, the metrics used to characterize impacts are generally closely linked to the methodological frameworks that developed them. The most used metrics are related to taxonomic richness or taxon abundance:

- **Potentially disappeared Fraction of Species** (PDF, Goedkoop & Spriensma, 1999) which predicts the disappearance of species due to an environmental pressure in a certain area, over a certain time (ReCipe[1]).
- **Mean species abundance** (MSA), which can be used as a State Indicator Metric as well as a Footprint metric. It is based on the intactness of ecosystems through the assessment of the originally occurring species abundance in a specific area compared to their abundance in an undisturbed reference.

Kuipers et al (2025) showed that these two metrics are not totally aligned: based on empirical data, PDF leaves about half of the variance in MSA loss unexplained. The two metrics reveal distinct aspects of community change: MSA reveals that abundance loss precedes species extinction, being more sensitive for biodiversity change than PDF, particularly at low PDF value.

In another assessment of methodology, Damiani et al (2023) showed that none of the 64 methods they reviewed in a sufficient way consider the entire variety of pressures on biodiversity, ecosystems, taxonomic groups or essential biodiversity variables classes. Moreover, Avila-Ortega et al (2025, under review) observe that metrics focus on taxonomic and functional diversity, mainly at a species level, with very few extended to ecosystems assessment and none to genetic diversity.

The wide variety of non-standardized methods for assessing impacts on aquatic biodiversity constitute an obstacle to impact assessment in LCA framework. Rubtsov (2024) suggests using estimates of biodiversity measures through eDNA analyses in LCA models, but no standard characterization factors (CFs) are yet available for aquatic biodiversity.

3.2.1.4 What pressures are considered in freshwaters biodiversity LCIA?

According to Damiani et al (2023), **Land Use** (LU) is the most assessed pressure in the LCIA methods, while water consumption, GHG or chemical pressures are less common; they found that only 11 methods apply to freshwater ecosystems, with only 5 out of them performing well (ReCipe 2016, LC Impact, Impact World+, GEP, PBF).

As impacts on biodiversity in LCIA were assessed mainly through land use changes, freshwater biodiversity was until recently only partially concerned. Quandt et al (2022) identified and classified in 5 categories (physical, mechanical, chemical, biological, other), 18 anthropic disturbance factors affecting freshwaters biodiversity depending on occurrence, intensity, duration and frequency. They showed that 8 out of these 18 factors (44%) are at least partly addressed in LCIA methodologies, while the others are not covered at all yet (see table 1), and they called for research developments.

[1] LCIA : le modèle ReCiPe | Le RIVM

Table 1. Freshwater biodiversity threats covered or not in LCIA, after Quandt et al, 2022. In bold, those that can be at least partially linked to HPP.

Freshwater biodiversity threats	
At least partly covered in LCIA	Not covered in LCIA
Thermal pollution (partially) Ionizing radiations Eutrophication / nutrient inputs Organic material (partially) Acidification Toxic substances (included pathogenic) **Water consumption** **Global warming**	Ozone depletion (only for human health) **Water flow alteration (including lateral and longitudinal fragmentation)** **Degradation of riparian banks** Freshwater salinization **Suspended sediments** (soil erosion) Microplastics **Invasive species** Overfishing Light and noise pollution

According to Mir et al (2025) only three methods allow the assessment of **water consumption** (WC) on freshwater biodiversity by developing specific characterization factors (CFs); two of them are linked to fish population reduction (Hanafiah et al, 2011; Pierrat et al, 2023a), the last one being linked to hydropower and loss of aquatic biodiversity (Humbert & Maendly, 2008). The most recent water footprint impact assessment involved the integration of water scarcity and pollution, and it was shown that pollution impact on biodiversity was more important than scarcity impact, especially for sensitive species and ecosystem (Pierrat et al, 2023b).

Water consumption impacts **aquatic habitat** characteristics and availability for biota. A model has been developed to quantify habitat change potential (HCP) due to water abstraction on a LCIA basis on French rivers (Damiani et al, 2019). The model considers physical habitat suitability for 8 fish species, 4 fish guilds and benthic macroinvertebrates; it has been applied on more than 114000 river reaches (mean length 24,7 km) and calculated for Q50 (median flow) and Q90 (dry flow). In addition to the reach scale characterization factors were aggregated at different spatial scales; HCPs at reach scale are weighted by the relative river length against the total length of watershed river segments. Weighted habitat surface represents therefore the habitat frequency in the watershed. It is positively correlated to the probability of habitat alteration at watershed scale due to water consumption, if site specific information is not available. Despite model uncertainties, the authors underline the necessity to complement a LCIA with this kind of model to better assess the impact of water consumption on aquatic biodiversity. The model was extended to world[2] rivers by Damiani et al (2021), using general hydraulics characteristics of rivers (watershed, slope, Strahler order, calculated depth and width, substrate diameter, Q50 and Q90).

Li et al (2022) developed spatially differentiated characterization factors (CFs) for the impact of **increasing water temperatures** on freshwater fish species due to climate change. They are expressed as PDF due to lethal and sub-lethal effects on fish. However, these CFs cannot be applied to assess impact of cooling waters.

Research is ongoing, to assess the impact of pressures on aquatic biodiversity linked to river fragmentation (see §3.4) but no literature is available yet for quantification of alien invasive species introductions in the LCIA framework for freshwaters biodiversity.

[2] In reality due to database information, it is limited to rivers under 60°N.

3.2.2 Framework for the assessment of HPP pressures on aquatic biodiversity

As mentioned above, **fragmentation** is one of the most evident pressures of hydropower on aquatic ecosystem (as well as other anthropic activities that need dams such as irrigation). At a global level, fragmentation has the second-largest impact score after water consumption (Figure 2). It may be slightly different at regional scale, depending on the importance of water consumption, that can be different in southern and northern Europe, for instance.

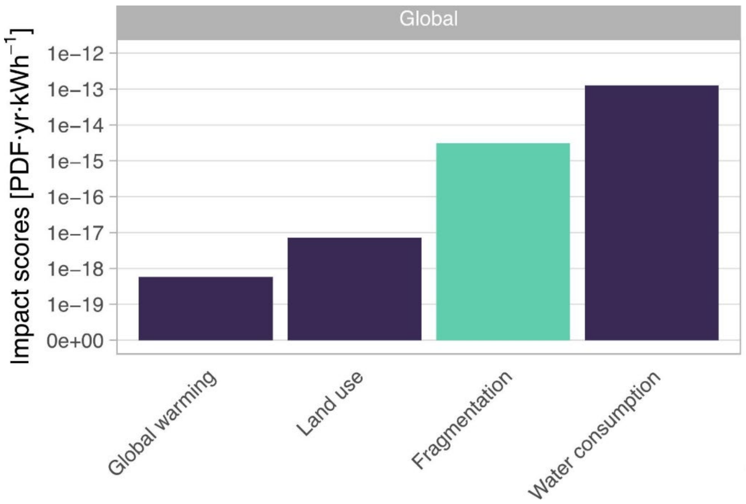

Figure 2. Impact scores in PDF.yr.kWh^{-1} expressing global species loss for 1 kWh of hydropower for the impact categories of land inundation, global warming, water consumption and fragmentation, (De Visser et al, 2025).

De Visser et al (2025) recently filled a gap in LCIA approaches by developing the first characterization factors for freshwater fragmentation, quantifying the isolation effect for freshwater fish species. It is based on a macro-ecological relationship between the range size and the body size based on 4162 non-diadromous fish species (Keijzer et al 2024) extended to 7369, which is used to assess if an isolated reach is big enough to sustain the species development and define the Minimal Viable Range Size (MVRS). It is expressed with PDF metrics. It is established at a global scale for 58811 watersheds. All dams are supposed to be impassable (low efficiency of fish pass, reservoirs barriers for downstream migration, less than 2% of low height dam recorded in the Global Dam Tracker database (GDAT, 31870 dams) …). This limited framework due to biases of global dam databases should be improved by better integrate small dams (<10m) and efficiency of fish pass. Also, the authors underline that MVRS estimates may be overestimated in smaller basins and overestimated in bigger ones.

Regarding the impact of reservoir occupation on macroinvertebrate richness, at different scales (reservoir, ecoregion and state), Trottier (2021) determined regional characterization factors and showed that they were pertinent at representing the impact at all scales. It was therefore possible to elaborate a model which was based on altitude, trophic state and surface of the reservoir, to assess the PDF when macroinvertebrate data are not available.

4 Framework for categorizing pressures

4.1 Hydropower pressures

The framework for hydropower pressures on aquatic biodiversity is synthetized in Table 2.

4.2 Refurbishment or new projects?

This framework for selecting indicators for an eco-design objective can be useful both for a new scheme and for refurbishment of an existing one.

The pressures and indicators used for this assessment will depend on:

- **The level of accuracy or knowledge of local environmental data**: this is likely to be well documented for an existing structure, but less accurate for a new project in the early stages of development, where only public data or preliminary field surveys may be available.
- **The type of refurbishment**: in many cases, refurbishment will not require large-scale construction work, and it is highly likely that such an assessment will not be necessary or at least will not need to cover all categories of pressures.

The indicator matrix will therefore be applied with the sole objective of identifying the eco-design levers for the project (new or refurbishment) and will be highly dependent on the site and type of project.

ReHydro's T5.6 aims to test different indicators in the demonstration sites by comparing the situation after refurbishment with the initial scheme. The approach will be based on identifying relevant indicators and pressures for each type of project, thereby validating *a posteriori* the expected and modelled improvement in biodiversity linked to the refurbishment project.

This validation will confirm the relevance of the indicators selected for assessing the impact of refurbishment on biodiversity.

Table 2. Effects on biodiversity linked to different type of hydropower local and global pressures

Pressure	Type of Alteration	Local/Global	Direct Effects	Indirect Effects
Fragmentation of watercourses	Longitudinal and lateral	Local	Inhibits access to essential habitats	Alters solid transport continuity and modifies the riverbed
Flow alteration →Habitat alteration	Physical pressure combination	Local	- Frequent (intraday) and rapid variations of flow (hydropeaking) - Seasonal phase shift between hydrology and organisms' needs	- Change in flood regime (e.g., lower frequency of channel-forming flows) - Flow reduction impacting wetted area, hydraulics, and habitat availability (e.g., spawning grounds)
Riparian and terrestrial habitat alteration	Dams and hydrological regime changes	Local	- Flooding of land areas by large dam reservoirs - Creation of lentic/lake areas instead of lotic zones	- Reduced flooding frequency in riparian zones downstream dam - Lateral disconnection of banks - Reduced flooding of alluvial plains or hydraulic annexes
Land use	Land transformation	Global	Through material extractions (gravels for concrete, steel, copper...)	Through transport of materials to the processing industrial plant or to the project site, etc.
Climate change	GHG emission	Local / Global	Reservoir emission during the entire operating phase as well as local works	Material extraction and transformation
Water consumption[1]	Reservoir evaporation	Local	—	- flow reduction in hot / dry periods
	Works	Global	Through materials extractions and transformation	—
Water quality[2] alteration Or pollution	Mainly thermal	Local	Cooling or warming of water	—
	Eutrophication, Toxicity	Global	Through materials extractions and transformation	—
Alien invasive species	Works and watershed connections	Local	—	Facilitation of species spread between previously isolated watersheds

[1]: flow reduction in by-passed sections is not considered as a consumption, but as a hydrologic alteration.

[2]: Other pressures (pollutants, eutrophication...) are not attributable to hydropower but to anthropic activities in the watershed.

5 Indicators to be tested on demonstrator sites

5.1 Global indicators

All the identified pertinent hydropower global pressures can be estimated via global indicators in quantitative analysis in LCIA.

Table 3. Global indicators in LCIA for hydropower pressure

Category	Pressure Indicator	Characterization models
Land Use	m^2 (occupied, converted)	Globio & ReCIpe
Climate Change	tCO_2eq (emission)	LC-Impact
Water consumption	m^3 (consumption)	Aware
Water Pollution	Kg $NO_2eq.$ (emission)	Impact World+

5.2 Local indicators

They are many indicators to assess the relevant pressures identified in 4.1. They may require detailed, or complex data, and may concern different components of the biodiversity.

As we want to compare project alternatives (or an initial state compared to a new scheme or to the refurbishment of an existing scheme), we have chosen to use the most general indicators, that can be fed with public data or data that relatively easily can be acquired through light field work. As much as possible, the chosen indicators are published in scientific literature or issued from WFD works or other European projects. The consequence is that the indicators and their combination will be widely applicable to European rivers and hydropower plants.

The indicators are listed in Table 4 and 5, next pages. Their assessment and pressure classes level (high, medium, low), as well as their limitation due to available data, will be tested in the next steps of T5.6.

They are described for each pressure they represent; **Fragmentation, Hydrology and Habitat alterations, Riparian and terrestrial habitat alterations, Water consumption, Pollution, and Alien invasive species (IAS)**

Note that some indicators assess similar impacts (e.g. F1 and F2; R3 and R4) and some other indicators cover mixed pressure (e.g. F1, F7); their feasibility and interest will be tested to retain the most pertinent and realistic in a eco-design approach.

The local indicators will be assessed in three impact levels (low, medium, high). They will be grouped by pressure categories, that can be related to IPBES categories, but no aggregation between categories will be done.

Table 4. Proposed Local indicators to be tested on site demonstrators for Local Fragmentation and Flow or Aquatic habitat alterations

Pressure	Pressure description	N°	Indicator	Reference
Longitudinal fragmentation	Artificial barriers (weirs, dams) may prevent **aquatic species** from completing their life cycle (upstream and / or downstream fish migration)	L1	Nb of barriers in the river (/km or /river section)	Van Treeck et al, 2022 (Tab 15-2)
		L2	Cumulative length of reservoir (/river section)	Van Treeck et al, 2022 (Tab 15-2)
		L3	Barrier effect (=1 – Lrest/Lref) *Lrest=river length to the 1st anthropic new barrier; Lref= total river length to the 1st natural barrier.*	From Sandlund et al, 2013 in Harby et al 2018
	Incoming **Solid transport** of gravel or fine sediments is totally or partially reduced.	L4	Water storage capacity: Long-term capacity ratio (LCTR)[3]	IHA, 2019
		L5	Dam transparency (to the total incoming sediment transport) *(combine transiting over incoming volume or granulometry and frequency)*	Malavoi & Loire, 2019
		L6	Barrier effect (see F3)	-
Lateral fragmentation	Lateral artificialization reduces the exchange of nutrients, **sediments and biological** materials between the riparian zones and the river or the floodplain and the river	L7	River incision (m)	Harby et al, 2018
		L8	% of artificial banks (except for bedrocks rivers)	Harby et al, 2023
Global Fragmentation	**Isolation effect** for freshwater fish species	L9	Minimum Viable Range Size (only for dam >10m)	De Visser et al, 2025
Flow alteration	**Hydropeaking** modifies magnitude, timing and frequency of flows, which impact organisms directly and through habitat alteration (short-term alteration)	F1	Hydropeaking tool (*combine sub-indicators, as magnitude, ramping rate, timing,…and vulnerability of the fish populations)*	FitHydro
		F2	Habitat vulnerability x Flow Hazard Index *(combine flow index from Courret, et al 2021 and Habitat vulnerability index for stranding or spawning dewatering or drift)*	Terrier et al, 2018
	Hydropeaking modifies the river's flow regime which disrupt the river's channel in the long-term	F3	Nb of flow variations x amplitude variations, related to characteristics flow (mean annual flow, biennial flood…)	Inspired by Courret et al, 2021
	Storage disrupts the natural flooding and low-water cycles, which impact biological life cycle	F4	10 years flood flow *(amplitude of changes in flood return period)*	Harby et al, 2018, Table 25
		F5	Seasonal regime shift (deviation to the natural regime)	Inspired by Ollero et al, 2011 and Harby et al, 2018
	Diversion of water modifies flow regime in the by-passed section which reduces wetted area (see also R2 and H1)	F6	Value and Regime of flow compared to ecological flow or to natural minimal flow (%)	Partly from Pierrat et al, 2023a

[3] LCTR : ratio between long-term reservoir volume (with or without sediment management) and initial reservoir volume (LCTR = 1 : no sediment accumulation)

Table 5. Proposed indicators to be tested on site demonstrators for Local Habitat alteration (Riparian and Aquatic), Pollution and IAS pressures

Pressure	Pressure description	N°	Indicator	Reference
Degradation of Riparian zones	Drying-out of **by-passed sections** results in watercourse width reduction, which impacts riparian functionality and favour terrestrial habitat	R1	Reduction of floodplain area or riparian width (%) (except for bedrocks rivers) *(analysis from historical map/aerial photos or expertise through F4 indicator)*	Partly from Dehédin, 2012
		R2	Wetted surface reduction (m^2, %) at low flow (e.g. percentile 10) combined to annual flow (*to be tested to complete L7 and L7 indicators)*	Inspired by Quick et al, 2017, and Moldoveanu et al, 2017 and 2023
	Flooding upstream dam impact terrestrial habitat and biodiversity.	R3	Loss of terrestrial surface (%)	-
		R4	Loss of terrestrial surfaces weighted with ecosystem types, through quantitative analysis (Land Use, LCIA)	Dorber et al, 2020
Degradation of aquatic Habitat	**Diversion** of water modifies wetted area and hydraulics, that impact habitat availability and quality.	H1	Habitat change potential *(this indicator combines hydraulics modification as well as substrate modification due to storage effect of dam)*	Damiani et al, 2021
	Flooding upstream dam replaces aquatic biodiversity*	H2	Length of inundated running watercourse (% of the river section)	Van Treeck et al 2022 (Tab 15-2)
Mixed Pressure on Fish	The local pressure of hydropower on aquatic biodiversity is the results of the **combination** of physical processus and vulnerability of species	H3	EFHI indicator *(takes into account the barrier effect on up/downstream migration, turbine impact and flow alteration).*	Van Treeck et al 2022 (EFHI)
Pollution	Deep reservoirs present **seasonally thermic stratification**; depending on the local context, the downstream section of the river may be impacted by cooler or warmer waters	P1	Warming waters *(LCIA quantitative analysis adapted to local pressure)*	Raptis et al, 2017
		P2	Warming combined to water reduction *(LCIA quantitative analysis adapted to local pressure)*	Pierrat et al, 2023b
		P3	Seasonal thermic differences (%) (+ or -) *(adapted to vulnerability of local species)*	-
	Eutrophication of reservoirs due to anthropic activities in watersheds may alter the water quality downstream	P4	(risk of) Deoxygenation of hypolimnion (% O_2) *and/or comparison of water quality (status) downstream to upstream*	-
	GHG emissions by reservoirs	P5	G-res tool *(in addition of LCIA analysis realized in global pressure assessment)*	Prairie et al, 2017.
Invasive Alien Species	IAS may be introduced through basin transfer or with works. They can deeply affect native biodiversity	A1	Nb of fish IAS introduced	-

* Lentic species are favoured at the expense of lotic ones. It is considered as a degradation of a natural situation (new lake species can sometimes colonize the up/downstream watercourse (degrading its functionality). Therefore, we chose to consider the new aquatic biodiversity not as a positive effect.

5.3 Quantification of the global indicators

The data required for LCIA must be sufficiently detailed and accurate to constitute relevant assessments; such data is generally available too late to introduce eco-design levers into the project design.

This is why it is proposed to evaluate, via demonstration sites, if assessments based on *ex-ante* estimates, even simplified or imprecise ones, can be used to identify areas for improvement in a project (both new and refurbishment projects) in terms of its overall impact on biodiversity.

The VSM demonstration site is the one that requires the most work (construction of a cavern and an underground circuit for the installation of a pump-turbine at the Saut Mortier dam). It is therefore the most suitable for testing the relevance of the proposed simplified global indicators.

We plan to do:

- A LCA of the works, based on matter and energy fluxes data coming from the detailed preliminary design study compared to the real data during the works ("Planned LCA" vs "real LCA")
- And in a second step, sensibility analysis to simplify the quantitative assessment as much as possible to select the minimal detail data required to correctly assess the impacts ("planned LCA" vs "simplified balance").

5.3.1 Planned versus real LCA

This phase will validate if the estimated quantities from the *ex-ante* measurements correctly identify the main pressures on biodiversity (correct prioritization of the contributions of the different phases of the project to the impact, for each of the four main pressure categories: **Land Use, Water consumption, Pollution, Climate Change**).

For instance (see Figure 3), the estimate based on *ex-ante* data from the VSM project shows that the construction of the new pump-turbine cavern is the main contributor to climate change pressure (58%, two-thirds of which is due to the cavern), followed by the recalibration of the Ain River (24%), preparatory works for the construction site (12%, mainly the development of access roads, a bridge and roads) and then general consumption (5%, employee travel) (Bouvier & de Becdelievre, 2024[4]).

[4] As the LCIA has been realized only for "works" steps, and in respect to the Energy and Climate French law, and to European recommendations about Environmental footprint methods, the main indicators that have been considered are Climate change, Pollution (acidification, freshwaters eutrophization, ozone depletion) and Resources Depletion (fossils and minerals resources). This LCIA will be completed for Water Consumption and Land Use impacts for the need of ReHydro.

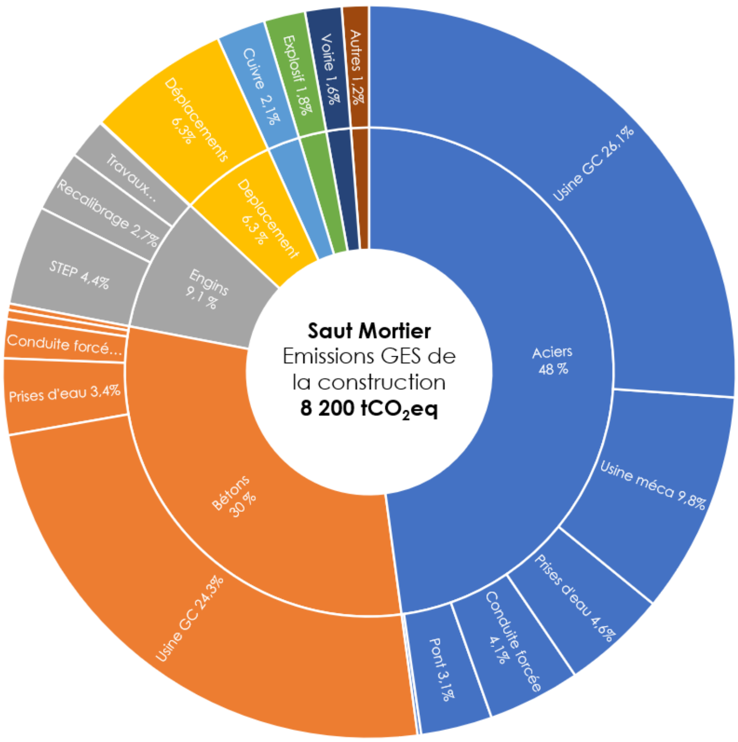

Figure 3. Contributions of VSM construction phase to climate, based on matter and energy fluxes estimated in the preliminary design study ('Planned LCA'). Fluxes that are considered are shown in Figure 4. (From Bouvier & de Becdelièvre, 2024))

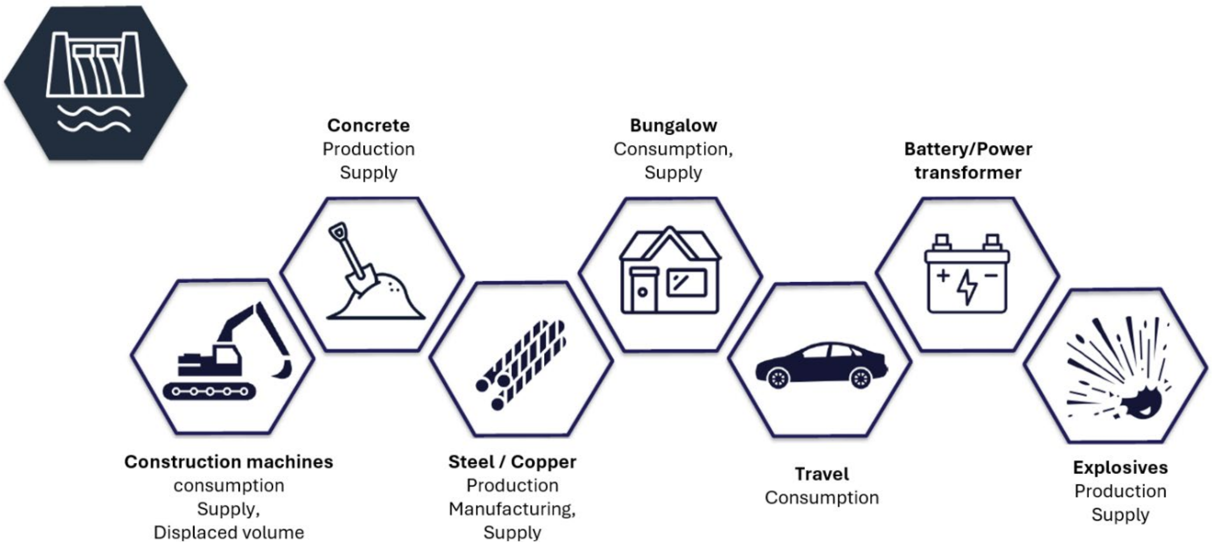

Figure 4. Matter and energy fluxes considered in the LCA assessment, in view of inter-comparisons depending on the data accuracy (estimated vs real) and method (LCA or simplified balance, considering only pertinent hydropower pressures). (From Bouvier & de Becdelièvre, 2024)

As the construction work will be carried out in part after the end of ReHydro, it is planned to compare the ‘planned vs. real’ results for the construction phases that will be carried out. This analysis will verify that the impact estimates based on the measurement data available at the project development stage correctly identify the pressures contributing to the impacts on overall biodiversity.

The conclusions relating to the main contributing pressures will be compared with those of the renovation of the Poutès dam[5] on the Allier River in terms of biodiversity. Barillier et al, in prep, showed that for this project, the main pressures causing the impact on overall biodiversity were due to land occupation and transformation as well as toxicity (climate change and water consumption pressures being little affected by the renovation).

5.3.2 Planned LCA versus Simplified balance

Depending on the previous results, we will try to simplify the inventory data required for a reliable assessment of the impacts hierarchy. For instance, this simplification may concern the accuracy of materials or engine types used for the constructive phase, by using standardized verified data available at EDF or industry partners.

The comparative analysis (‘planned’ vs ‘simplified’) will be conducted on VSM database, after the validation of the previous analysis (‘planned’ vs ‘real). It will allow to retain relevant simplified tools whenever possible, instead of a LCA, which are time and accurate data consuming.

[5] For information about Poutes dam refurbishment, see https://amber.international/portfolio-item/poutes-dam-river-allier-france/

5.4 Test of the local indicator matrix

We propose to test the feasibility and relevance of the indicators on the different demonstrator sites or sites proposed by partners. Depending on the refurbishment projects, not all the indicators are relevant (Table 6).

Table 6. indicators to be tested on site demonstrators

Pressure	N°	VSM	Rhone	Röldal-Suldal	Lima (EDP)
Longitudinal fragmentation	L1	X	X	?	X
	L2	X	X	?	X
	L3	X	X	?	X
	L4	X	X	?	-
	L5	X	X	?	-
	L6	X	X	?	-
Lateral fragmentation	L7	X	X	?	-
	L8	X	X	?	-
Global Fragmentation	L9	X	X	?	X
Flow alteration	F1	X	X	X	X
	F2	X	X	X	X
	F3	X	X	X	X
	F4	X	X	X	-
	F5	X	X	X	X
	F6	X	X	X	-
Degradation of Riparian zones	R1	X	?	X	-
	R2	X	?	X	-
	R3	X	?	X	-
	R4	X	?	X	-
Degradation of aquatic Habitat	H1	X	?	X	-
	H2	X	?	X	-
Mixed Pressure on Fish	H3	X	x	X	X
Pollution	P1	X	X	?	X
	P2	X	X	?	X
	P3	X	X	?	X
	P4	X	-	?	?
	P5	X	X	X	X
Invasive Alien Species	A1	X	-	-	X

6 Conclusions - Perspectives

The proposed approach aims to ultimately develop a tool for assessing the biodiversity footprint of hydropower. It does not replace ecological methods but attempts to integrate the impacts of projects across their entire value chain and life cycle.

This approach is useful both for helping in the choice between different renovation options and for assessing whether the impact generated by the renovation work is lower than the ecological benefit that this renovation will bring. The difficulty of the exercise lies in the fact that it is necessary to base a tool of this type on tools from distinct disciplines: environmental sciences, energy sciences, and materials science for global indicators (LCA), and ecology for local impacts.

As with any model, there is a great deal of uncertainty associated with these assessments. Moreover, not all pressure yet benefit from simple impact models. A final challenge lies in the fact that the input data must be sufficiently simple to acquire but representative of the impact, as the tool is designed to be used in the early steps of a development.

The indicators proposed here are the result of a literature review and the expertise of the partners, who are mainly from the ecological sciences.

Next steps will be to test and select the most relevant local indicators that will be able to complete the global indicators, even with undetailed data. These local indicators have to show their capability to discriminate and correctly represent the impacts, based on experts' advice.

Their inter-operability with existing indicators (CSRD) will be assessed; to finally build a methodological framework able to calculate a biodiversity footprint index (WP5) that will be useful to eco-design future hydropower refurbishment projects (WP6).

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