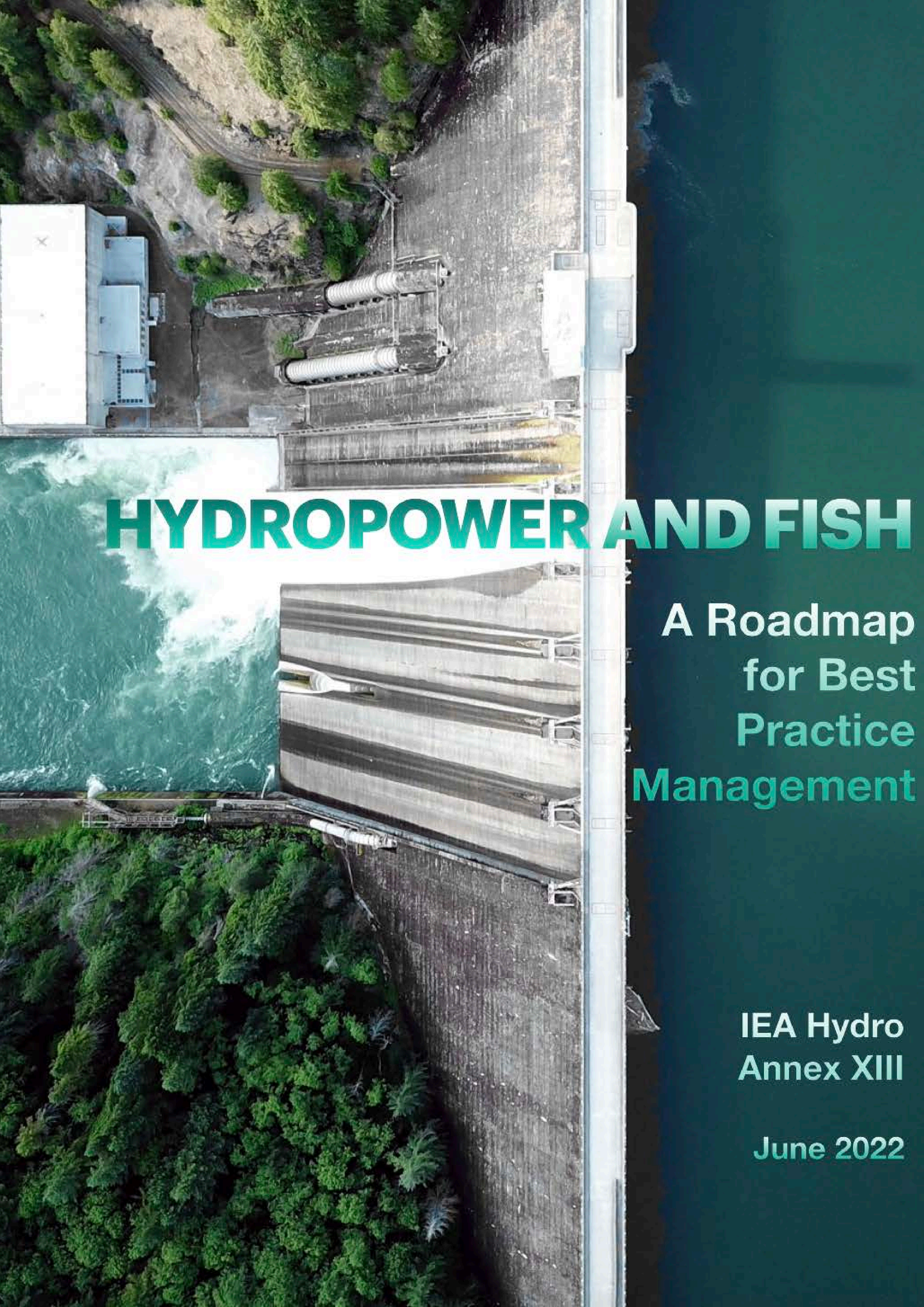

HYDROPOWER AND FISH

A Roadmap for Best Practice Management

IEA Hydro
Annex XIII

June 2022

In loving memory of Hans-Petter Fjeldstad

The Roadmap is dedicated to the memory of Hans-Petter Fjeldstad. Our dear colleague and friend sadly passed away aged only 53 years, in March 2020. Hans-Petter was Norway's top expert in fish migration solutions, combining hydraulics and river science with biology. With his background in civil engineering and a Ph.D. in fish migration solutions, Hans-Petter always sought solutions to help fish migrate past barriers. He combined strong scientific knowledge with an inventor's approach to practical applications, often leading to innovative solutions. He served as an engaged, inspirational, and knowledgeable advisor to many hydropower operators, energy and environmental authorities, and fishing and landowners' associations. He contributed to several expert groups, giving advice and recommendations. His research resulted in numerous publications, reports, and advice on how to take care of the environment in hydropower rivers. When Norway proposed the new Annex XIII on Hydropower and Fish in 2013, Hans-Petter was the natural choice to be nominated as the Operating Agent. He continued to coordinate the work of this Annex even as fighting cancer took up more and more of his strength. He truly appreciated international collaboration - to have peers learn from each other and find even better solutions together.

Hans-Petter kept his humour, positive attitude, and great interest in caring for fish and nature in hydropower rivers until the very end. He was not only a friend of fish and salmon in nature, but Hans-Petter also cared a lot for the people around him. He was especially dedicated to helping advise and encourage young colleagues and early career scientists – always with a touch of humour combined with support and useful advice.

Much of Hans-Petter's research is now key knowledge to finding good solutions and is a great inspiration for further research and development in the challenging field of fish migration.

This Roadmap was initiated and first outlined by Hans-Petter. It builds on his knowledge and network initiative, and we are all very thankful for the journey we have been on with him. Hopefully, this Roadmap proves further Hans-Petter Fjeldstad's inspiring research and engagement.

THE INTERNATIONAL ENERGY AGENCY TECHNOLOGY
COLLABORATION PROGRAMME ON HYDROPOWER

IEA Hydropower

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I would like to express my sincere gratitude to everyone who contributed to this report on the challenges that hydropower development may pose to inland fish populations. This Roadmap may serve as a valuable resource to practitioners in the hydropower sector, and it wouldn't have been possible without the dedicated work of so many individuals from around the world.

First and foremost, I want to thank the chief Operating Agent of Annex XIII, Hans-Petter Fjeldstad, for his coordination of the Annex activities since 2014. Over the years, his fruitful collaborations and dissemination on a scientific level, as well as on a personal level, within Annex XIII have been invaluable. We all miss him.

I would also like to thank Niels Nielsen, former Executive Committee Secretary of IEA Hydro, who provided invaluable support and spent countless hours accomplishing the Roadmap in its current form. Lori Nielsen, as well as my senior colleague Atle Harby, played important roles in the project by aiding assistance and guidance. I am also grateful to the communication department of SINTEF Energy, Eline Opdalshei, Astrid Benedicte Lundquist and Daniel Albert for their gracious help in the final formatting of the document.

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I am also grateful to Alex Beckitt, Chair member of the IEA Hydro TCP, and Klaus Jorde, Executive Secretary of IEA Hydro, for the supportive environment within IEA Hydro. And lastly, I would like to acknowledge ChatGPT and its developers, who provided valuable suggestions to improve the acknowledgement section of this document. Such technology truly has the potential to improve our work.

Finally, I would like to express my gratitude to the Norwegian Research Council for its financial support to my work. Without the contributions of all these individuals this report would not have been possible.

Marcell Szabo-Meszaros
Operating Agent of IEA Hydro Annex XIII
24 March 2023

Abstract

The development of a hydropower facility has, in nearly all cases, some impact on natural river flows and the wider environment. This impact often includes the effect on fish, most notably curtailment of migration routes and changes to their natural habitat and ecosystem services fish is dependent on.

The general relationship between fish and hydropower development and management has been the subject of extensive research for many years. However, most of the previous work has been based on a limited number of species, with the applicability of results on a global scale difficult to justify. With the further development of hydropower planned on a global scale, a program of international collaborative research is justified.

This document identifies emerging best practices for managing hydropower and fish, by addressing relevant measures to mitigate changes in hydro-morphological conditions, water quality and quantity due to hydropower development. Where relevant, some of the most mature solutions are described as providing safe two-way connectivity for fish past barriers created by hydropower infrastructures. As such, it serves as a valuable resource for practitioners in the hydropower sector by providing a clear pathway toward viable solutions to the identified challenges for fish and hydropower.

Technical solutions that establish connectivity or mitigate other impacts of hydropower on fish have been used for over a century, providing valuable lessons for implementing effective measures. Innovative technologies based on R&D are continuously emerging to preserve native fish and their habitats on hydropower-regulated watercourses. With the continued global expansion of the hydropower industry, including the development of new dams and renovation of existing ones, and revision of old schemes, there is a pressing need to establish a consistent framework based on understanding the impacts of hydropower on fish, with a focus on improving the decision-making process for designing and implementing relevant mitigation measures.

This Roadmap addresses this demand by presenting a multi-phased process to evaluate the need for fish passage facilities and other solutions at new and existing dams under prevailing policies, integrating a holistic approach to assess key components of dam design and ecological needs. The framework suggests an approach that begins with an analysis of the existing policies and requirements for addressing the impact of hydropower on fish in the country, or region, of a dam of interest. Understanding the legal requirements for mitigation measures is the first step in informed decision-making.

The Roadmap starts with a broad background to hydropower and fish, followed by conflict descriptions between them. Where there are challenges, the Roadmap provides sustainable options in terms of mitigation measures for further consideration. Since there is often more than one suitable alternative that shall be investigated together with local experts, decision-support processes guide and assist the reader in carefully considering mitigation options; flowcharts with explanations of their application support this process. The final important step is an operational monitoring program with various techniques that evaluates the effectiveness of the performance of the selected mitigation option. Although the main focus of the Roadmap has been to provide relevant and effective sustainable solutions for fish populations, many of the same measures may also be beneficial for viable habitats and hence for other aquatic species.

Abbreviations

ADCP	Acoustic Doppler Current Profiler
BPV	By-Pass Valves
CBA	Cost-Benefit Analysis
CEA	Cost-effectiveness Analysis
CFD	Computational Fluid Dynamics
DO	Dissolved Oxygen
EIA	Environmental Impact Assessment
EIT	Ecologically Improved Turbine
EMP	Environmental Management Plan
ERA	Environmental Risk Assessment
EU	European Union
FGR	Fish Guidance Rack
GHG	Greenhouse Gas
HPP	Hydropower Plant
HSAP	Hydropower Sustainability Assessment Protocol
IEA	International Energy Agency
IHA	International Hydropower Association
MCA	Multi-Criteria Analysis
MGR	Minimum Gap Runner
ORM	Optimized Reservoir Management
PSP	Pumped Storage Plant
RBM	River Basin Management
ROV	Remotely-Operated Vehicle
TCP	Technology Cooperation Programme
TDG	Total Dissolved Gas
VRE	Variable Renewable Energy
WFD	Water Framework Directive

TABLE OF CONTENTS

THE INTERNATIONAL ENERGY AGENCY TECHNOLOGY
COLLABORATION PROGRAMME ON HYDROPOWER

IEA Hydropower

International Energy Agency (IEA)

IEA is an independent organization established in November 1974 in the Organization for Economic Co-operation and Development (OECD) framework. IEA is promoting a wide diversity of programs concerning energy cooperation among 31 countries of the 38 OECD member states (as of august 2022), such as:

- To maintain and improve a system for handling the oil supply disruption.
- To promote optimized energy policies against the current world situation through cooperative relationships with non-member states, industrial circles, and international organizations.
- To manage a lasting information system regarding the international oil market.
- To enhance the world energy demand-supply structure by developing alternative energy sources and improving energy utilization efficiency.
- To support the integration of environmental policies and energy policies.

The IEA Technology Collaboration Programme on Hydropower

The IEA Technology Collaboration Program on Hydropower (IEA Hydro TCP) is a working group of International Energy Agency member countries and others with a common interest in advancing hydropower worldwide. Current members of the IEA Hydro TCP are Australia, Brazil, China, the EU, Finland, Japan, Norway, Switzerland, and the USA. Sarawak EB is a sponsor. Member governments either participate themselves or designate an organization in their country to represent them on the Executive Committee (ExCo) and the working groups, also known as Annexes (renamed Tasks from June 2022), through which IEA Hydro's work is carried out. Annexes are coordinated by Operating Agents (renamed as Task Managers in June 2022). Some activities are collaborative ventures between the IEA and other hydropower organizations.

Vision: Through the facilitation of worldwide recognition of hydropower as a well-established and socially desirable energy technology, advance the development of new hydropower and the modernization of existing hydropower.

Mission: To encourage through awareness, knowledge, and support the sustainable use of water resources for the development and management of hydropower. To accomplish its Mission, the Executive Committee has identified the following program-based strategy:

- Apply an interdisciplinary approach to the research needed to encourage the public acceptance of hydropower as a feasible, socially desirable form of renewable energy.
- Increase the current wealth of knowledge on a wide array of issues currently associated with hydropower.
- Explore areas of common interest among international organizations in the continued use of hydropower as a socially desirable energy resource.
- Bring a balanced view of hydropower to the worldwide debate on its feasibility as an environmentally desirable energy resource.

Information about membership and research activities can be found on the IEA Hydro website: www.ieahydro.org

SECTION 1. INTRODUCTION AND OVERVIEW

Section 1 covers an introduction to the Roadmap in terms of its objectives and an overview of its purpose, scope, and structure. The section also identifies target groups and stakeholders who would benefit from its use and helpful terminology to support the text.

1.1 Objectives of the Roadmap

The overall Objectives of the Roadmap are to:

Establish a framework based on understanding the impacts of hydropower on fish, focused on improving the knowledge-based decision-making process for designing and implementing mitigation measures.

This Roadmap will document the development of a decision-making process to achieve this objective. This is especially important as a vehicle to review the challenges and needs of society as a component of the future development of hydropower. It is well known globally that hydropower facilities impact riverine ecosystems. The presence of a barrier across a river, in this case, associated with hydropower plants (HPPs), has the potential to create an issue (known) or risk (potential) to resident and migrating fish species and to the design and operation of the HPPs. These issues and risks can occur in the zones upstream of the barrier (i.e., reservoir, forebay, tunnels, or conduits) in terms of habitat changes, the barrier itself in terms of fish passage in both directions and downstream of the barrier with potential direct and indirect impacts from flow discharges. However, while impacts and risks are covered in general terms in this Roadmap, its prime purpose is to provide a decision-support system first to enable the selection of “target” fish to pass the barrier with a reasonable chance of survival and second to minimize negative impacts from hydropower on fish in general.

For many dam structures, technical and operational solutions have been implemented to establish or re-establish connectivity and ensure residual flow at the bypass reaches or mitigate diverse hydro-morphological conditions. For over a century, technical solutions such as fishways have been developed to provide upstream fish passage past some hydropower barriers. Innovative technologies have also been developed over decades to allow downstream migrating fish to pass safely and mitigate other impacts. However, there are also many hydropower developments where a safe fish passage was not incorporated into the original design or maintained to remain effective. With the continued global expansion of the hydropower industry, including the development of new dams and the refurbishment of existing ones (including retrofitting existing dams and reservoirs with hydropower facilities), there is a pressing need for the establishment of a framework focused on improving the decision-making process. In addition, a set of objectives for the design and ecological performance of new fishways are essential to address other challenges to the fish community posed by hydropower projects.

1.2 Purpose, Scope, and Structure of the Roadmap

This Roadmap comprises the work of the IEA Technology Collaboration Program on Hydropower (IEA Hydro). It is a deliverable of Annex XIII, Hydropower and Fish (official webpage of Annex XIII).

The Roadmap is based on the latest knowledge from Research, and Development works from involved project partners representing several countries from around the world. The Roadmap was prepared under the leadership of researchers from SINTEF Energy Research, with the support of participants of the IEA Hydro TCP and the help of the IEA Hydro Secretary. Meetings, workshops and participation at international conferences took place during the project; both face-to-face and online, where user partners contributed to the development, elaboration and improvement of the Roadmap. However, key actions are suggested by the leading research partners. They do not necessarily represent the view of all project partners.

1.2.1 PURPOSE

This Roadmap addresses emerging best practices that meet its objectives: to provide mitigation measures for fish at HPPs that minimize the impact of hydropower activities on the fish communities and habitats throughout the entire watershed. Fundamentally, the Roadmap leads the reader through best practices in identifying challenges, solutions, and the decision-making processes that achieve these objectives. The Roadmap also identifies a monitoring and feedback strategy to evaluate the solutions' effectiveness. However, notwithstanding the processes suggested in this Roadmap, any regulations for the relevant jurisdiction must be identified and adhered to.

This Roadmap presents a multiphase process to evaluate the need for fishways and other mitigation measures at dams either existing, under construction or undergoing refurbishment, based on prevailing or new policies. The approach is holistic, integrating key components of dam design, ecological needs, and existing policies covering the requirements for fishways in the country or region of the dam of interest.

1.2.2 SCOPE

The Roadmap addresses this demand for a framework by providing a specific plan of action through flowcharts to identify key challenges and potential solutions to manage them. Additionally, the framework includes a set of case studies from around the globe in the **Appendix** (available separately).

An essential aspect of the scope is the simple flowcharts developed to guide the reader in decision-making (Section 5). Following the issues described in fish communities caused by hydropower operations and regulations, the set of flowcharts has been compiled. The purpose is to provide a relatively simple tool for the reader to highlight the main steps to identify problems and define their potential mitigation measures. The reader can explore the potential challenges in most cases by providing basic information on the hydropower facility of interest. By accessing proper investigations, the user is assisted in following recommended practices. However, it must be emphasized that decision-support presented in this document only shows potential measures to address the different challenges. In contrast, experts must make final decisions based on local investigations.

To support the framework on the passage of fish past dams in both directions, the effects of impounding the watercourse, HPP management, and operation on fish and fish habitat are covered.

Overall, the Roadmap focuses primarily on addressing interactions between hydropower and fish. The challenges and the solutions are presented throughout the sections, as well as decision-support tools (flowcharts) with additional practical information. Although the focus is to describe the current best practices design for mitigating multiple impacts from HPP development and operation, many of the same measures would also be ecologically beneficial for other biotas.

1.2.3 STRUCTURE OF THE ROADMAP

The Roadmap is organized into six main sections. It starts with an introduction and background to hydropower and its impacts on fish. It then describes competing interests between hydropower and fish, combined with sustainable options and a section focusing on decision-making. The final section covers monitoring the effectiveness of solutions. References and two appendices complete the Roadmap.

The structure of the Roadmap is exemplified by the general overview, shown in Figure 1.1, and the full titles of each section, with a brief description, are presented below:

Section 1: Introduction and Overview

The document's first section provides a brief outline of the objectives set by the Roadmap. It states the document's scope, purpose and structure while clarifying the target audience. At the end of this section, the terminology is added to set a common level of understanding regarding terms used throughout the Roadmap.

Section 2: Background

This section summarizes the background to the main aspects addressed by the Roadmap. It starts with the history of modern hydropower utilization and how it plays an important role in our society while stating the essential nature of riverine ecosystems. The section highlights how hydropower development on a watercourse interferes with native fishes. Next, it shows the importance of legislation in the sustainable use of hydropower, which may set a threshold for maximum impact on the targeted fish species. Examples are provided on hydropower legislation, impact assessment, and ecological aims.

Section 3: Hydropower and Fish: competing interests

Section 3 starts with classifying hydropower installations and their operational strategies. Next, it presents through five processes the main changes on inland watercourses that hydropower facilities may induce, which cause challenges for aquatic ecosystems: these challenges are labelled as issues (which certainly occur) or risks (that may occur). This part describes the effect of i.) fragmentation and it discusses the other impacts caused by artificial ii.) impoundment, disturbed iii.) sediment transport, iv.) water temperature and water quality changes, v.) regulated flow and water abstraction. In addition, issues and risks associated with the construction phase of new hydropower plants or the refurbishment of existing ones are discussed.

Section 4: Hydropower and Fish: sustainable options

This section addresses the issues and risks of the five processes introduced in Section 3. To address fragmentation, solutions are discussed separately for upstream and downstream fish movement, emphasizing optimization techniques. A brief overview of the challenges is presented for the other four processes. It is accompanied by information on recommendations and possible limitations to remediation. The section highlights the importance of coordinated actions across the water basin while defining critical options for constructing or refurbishing hydropower plants.

Section 5: Decision-Making Processes

The section presents the decision-making processes and the developed flowcharts of the Roadmap, starting with an overview of the various existing methods for the economic analysis of mitigation measures. Next, the flowcharts, structured into multiple layers, are introduced together with guidance on how to use them to guide the reader toward suitable options to be considered. The processes and flow charts are structured according to the processes presented in Sections 3 and 4.

Section 6: Monitoring Effectiveness of Solutions

The last section of the document summarizes the different techniques to characterize and monitor the aquatic environment as well as fish movement and abundance. It discusses monitoring and assessment programs for fish passage, numerical tools for hydrodynamic models, and habitat evaluations. The section ends with a short overview of water quality monitoring techniques.

References

The references are found at the end of the document categorized by sections. Each section follows the same in-text citing format, e.g., [2.13] refers to the 13th reference within Section 2. References are listed in APA style.

Appendix

As a separate document, an **Appendix** accompanies the Roadmap with practical information, including reported studies from 11 cases with applied best practices from different hydropower plants. Next, it includes a list of guidelines from different countries for implementing various mitigation measures. In addition, a brief overview is provided for recent and ongoing projects from several countries addressing specific or multiple environmental challenges posed by hydropower projects. By the end of the appendix, a list of papers from a special journal session issued within the Journal of Marine and Freshwater Research in 2018 through collaboration with IEA Hydro Annex XIII is provided.

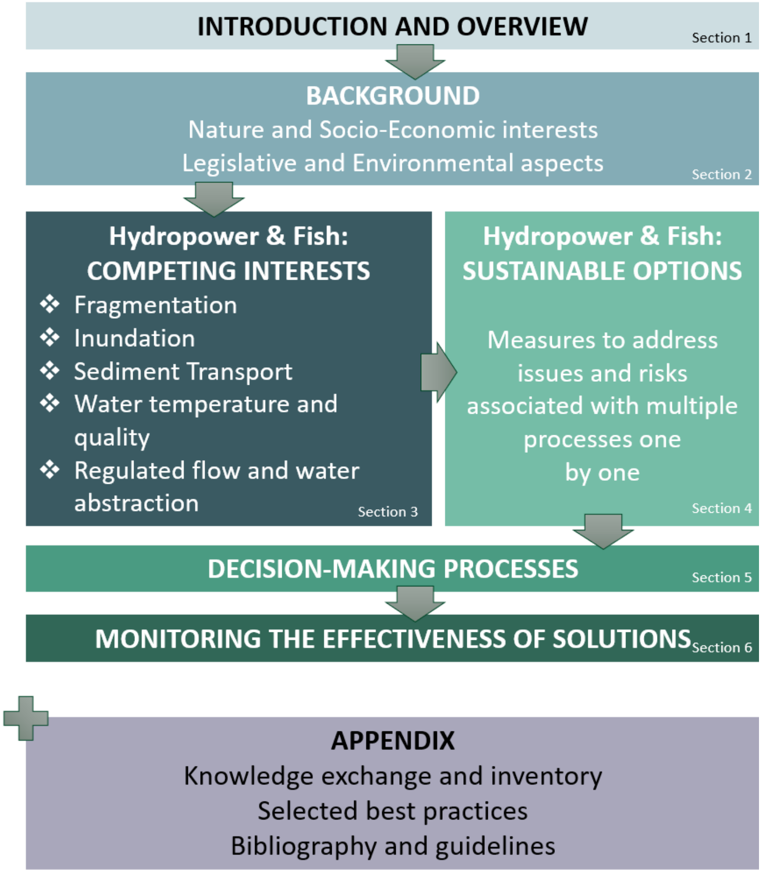

Figure 1.1***: General Overview of the Roadmap structure***

1.2.4 Target Groups and Stakeholders

The primary target groups of this Roadmap are practitioners, such as hydropower production companies, their staff, consultants, experts in relevant technical or natural-science fields, and regulators.

1.2.5 TERMINOLOGY

For this Roadmap, the following terminology has been adopted.

Connectivity

Connectivity acts on one temporal and three spatial dimensions: longitudinally from headwater to confluences and the sea, laterally from the main channel to floodplains, and vertically from the river towards the hyporheic interstitial and the groundwater. River connectivity is essential for maintaining freshwater ecosystems because barriers alter abiotic conditions and the biotic communities, compromising biodiversity, with a particular impact on long-distance migratory fish species.

Conservation

Conservation aims to maintain nature by enhancing ecosystem services and protecting biological diversity. It commonly focuses on ensuring healthy populations of fish, dynamic habitats and other biota-dependent hydro-morphological processes.

Decision-support process

A *decision-support process* is an information system that supports knowledge-based decision-making activities. It can serve the management, operations, and planning levels to enable people to make decisions about situations that may be complex, qualitative, and generally not easily specified. Decision support systems can be computerized, human-powered, or both.

Eco-hydraulics

Eco-hydraulics is an interdisciplinary science to study the relationships between the physical living space and corresponding aquatic ecosystem dynamics.

Ecological trap

Animals often use environmental cues to navigate between suitable habitats. It is termed an *ecological trap* when human-induced changes in a given environment may falsely lead some species to habitats where their fitness is lower than other available options. It is also associated with an increased risk of population decline.

Ecosystem services

Ecosystem services provide humans with several basic benefits from the natural environment with healthy ecosystems. They include services like vegetation that halt soil erosion, clean air, and withdrawn water; bacteria decompose biological substances; and animals circulate nutrients in natural processes, among others.

Environmental flows

Environmental flows (or e-flows) represent the quantity, timing, and quality of ecological flows required to maintain freshwater and estuarine ecosystems and the livelihoods and general welfare of people who depend on these ecosystems.

Fish movement and fish migration

Fish movement is the simple act of changing locations on a generally small-scale home range. At the same time, *fish migration* differs from repetitive and localized movements, as it often occurs on large spatial and temporal scales and follows a predictable seasonal pattern. For simplicity, the Roadmap uses *migration* as a primary term to describe the active displacement of fish on both small and large spatial scales.

Fragmentation

Fragmentation is when parts of a habitat are destroyed or changed significantly, leaving behind smaller unconnected areas. This Roadmap refers to the impacts of constructing a barrier (to utilize hydropower) on fish and their habitats within a watercourse.

Holistic approach

The ***holistic approach*** characterizes interconnected phenomena within an entire system where challenges must not be addressed individually but only through reference to the whole system. In the Roadmap context, conservational fish strategies within hydropower-regulated watercourses shall address identified issues and risks. It is also known as integrated river basin management.

Hydropeaking, thermopeaking and saturopeaking

Hydropeaking is when hydropower plants operate for short-term regulation of the grid or peak load production on demand to optimize the water volume available. It may cause artificial rapid flow/water level fluctuations downstream of the turbine outlet into the river with extremely low flow and sudden high flow situations. These rapid flow alterations differ significantly from natural flow changes and may lead to flushing and stranding of riverine biota. It is also known as flow pulses, ramping, or flow ramping. When released water from hydropeaking has a significantly different water temperature compared to the recipient watercourse, it is termed *thermopeaking*. If the released water from hydropeaking is supersaturated with gases, it is termed *saturopeaking*.

Impoundment

Impoundment (or *inundation*) is the intentional flooding of land, which would otherwise remain dry, for river management. In the context of the Roadmap, it refers to land flooding for electricity generation by hydropower, which occurs in lake reservoirs after damming or in pounded rivers (leading to more stagnant water).

Issues and Risks

Issues are defined as ecological impacts that have occurred or are known to occur. In contrast(ecological) *risks* may or may not occur and are presently unknown.

Mitigation measures

Mitigation measures, by definition, provide a system to prevent, minimize, or offset the potential negative impact of development activities on the environment. For the Roadmap, mitigation measures target the (potential or occurred) negative consequence of hydropower development on fish and their riverine environment.

Reservoir

A *reservoir* in this document refers to an enlarged natural or artificial body of water created by a dam to store fresh water. Such a reservoir can be created in many ways, including controlling a watercourse that drains an existing body of water, interrupting a watercourse to form an embayment within it through excavation, or building retaining walls or levees. It may be a lake type, typically for high-head reservoirs or an impounded river, more typical for Run-of Rivers reservoirs.

Residual flow

Residual flow is used as a general term in the Roadmap to cover a reduced discharge in a bypass section, independently of the following concept of such releases (i.e., either based on minimum, instream, or environmental flow concepts). It may also be the flow contributions from unregulated flow, e.g., from a side-tributary.

Restoration

Restoration is a process that aims to re-establish natural processes and increase biodiversity as much as possible in degraded, damaged or destroyed parts of an ecosystem as a result of human-induced activities.

Target Fish

Target fish corresponds to the representative fish species found in each freshwater environment that is being or will be altered by hydropower facilities. Representation by the selected group of fishes covers the various species with different swimming capacities, habitat requirements, feeding, and migration strategies, in their corresponding life stage(s), with their corresponding needs and abundance for sustainable use of hydropower. Beyond ecological reasons, social or economic interests may also contribute to the identification of fish species. They are termed focal specie and used to measure the impact of anthropogenic sources on fish.

SECTION 2. BACKGROUND

Section 2 presents the impacts of hydropower developments on fish. It starts with notes on social and natural aspects relative to watercourses, followed by a brief overview of the main interactions. The next part presents the policies and regulations that must be addressed, depending on the relevant jurisdictions. This is interlinked with environmental impact assessment and its role in evaluating the degree of hydropower impact on local fish. Based on the previous subsections, the final part discusses ecological aims: mitigation and conservation targets.

2.1 Socio-economic Interests: The Present and Future of Hydropower as a Renewable Energy Source

The rationale for hydropower is based on its past and present a significant contribution to global energy and its future importance towards a post-carbon civilization.

Hydropower is a long-standing, reliable, safe, and cost-competitive renewable energy source. It is essential in today’s electricity mix, contributing more than 17% of electricity generation worldwide and about 85% of global renewable electricity (International Renewable Energy Agency). The contribution of hydropower is twofold: the primary benefit is the generation of clean, low-carbon, and renewable electricity. The secondary benefit is that hydropower complements the intermittency and uncertainty of wind and solar energy.

Figure 2.1 ***Spill over run-of-river hydropower dam at Hunderfossen on River Gudbrandsdalslågen, Norway*** (photo credit: jstuij/shutterstock.com)

Hydroelectricity presents several advantages over most other electrical power sources (Figure 2.1). It has a high level of reliability, is a proven technology, has high efficiency, relatively low operating and maintenance costs, flexibility, and in many cases, a large reservoir storage capacity. Moreover, reservoirs associated with hydropower development are often used for multiple purposes, such as water supply, flood and drought management, irrigation, navigation, and recreational activities. These water management services often complement each other (for instance, a reservoir often used for flood mitigation can also store the water for hydropower generation at a later stage).

The future of hydropower as a safe, reliable, and renewable source of low-cost energy and flexible energy services is secured. Some future energy scenarios suggest doubling hydropower capacity by 2050 (International Renewable Energy Agency). In addition, the development of pumped storage hydropower could increase threefold. However, to achieve its considerable potential for increasing energy security while reducing reliance on electricity from fossil fuels, hydropower must overcome barriers related to policy, environment, public acceptance, market design, and financial challenges.

Most of the growth in storage hydropower generation will come from large projects in emerging economies like Africa, Asia, and Latin America. Large and small hydropower projects in these regions can improve access to modern energy services, help alleviate poverty, and foster social and economic development, especially for local communities.

The growth of hydropower in industrialized countries is likely to focus primarily on developing pumped storage projects and modernizing existing hydro stations. Smaller growth may come from adding power to non-power dams, increasing existing reservoirs by dam heightening, and creating other water infrastructure like adding new purposes to existing reservoirs.

2.2 Natural Interests: General Information about Fish, their Diversity, Lifecycle, and Migration

Freshwater Fish Diversity

Inland watercourses provide various services to humans while also hosting complex ecological niches, processes and high biodiversity. Fish are the most diverse vertebrates comprising *ca*. 57% of all identified species globally. Presently a total of 35,562 fish species are known to science, with 17,940 (*ca.* 50%) inhabiting freshwater systems [2.1]. This notable diversity of freshwater fish is distributed amongst six ecoregions in the world, with the Neotropical region (i.e., Central and South America and the Caribbean) presenting the highest variety (over 5,150 species) and the Australasian region (i.e., Oceania *lato sensu*) the lowest (*ca.* 580 species) [2.2][2.3]

Freshwater fish are classified into three groups based on salinity tolerance. This classification determines species' life histories and ability to colonize different habitats. Fish species are labelled *primary fishes*, with their distribution restricted to freshwater and, thus, intolerant to salinity. *Secondary fishes* are tolerant to saltwater and can occasionally transpose sea-water barriers. The third group is represented by *peripheral fishes* containing species of marine origin that have colonized inland (fresh) waters [2.2][2.4]. Several marine fish (i.e., anadromous fish) migrate to freshwater habitats to complete at least one life cycle stage in freshwater. Understanding the life history of fish species (their pattern of survival and reproduction, along with the traits that directly affect survival and the timing or amount of reproduction) gives us crucial information about their movement, migratory patterns, and ecological requirements.

Freshwater Fish Movement and Migratory Classification

It is essential to recognize that all fish must move or migrate between habitats during their life cycle. The nature of movement will depend on motivation, objectives, direction, distance, and fitness. Therefore, the conceptualization of movement and migration is essential to define strategies used by different species. The literature defines movement as simply changing locations within a generally small-scale home range [2.5]. On the other hand, migration differs from repetitive and localised movements within a well-defined home range. It often occurs in large spatial and temporal scales and is characterized by predictable seasonal and directional migration [2.5][2.6]. For simplicity, migration will be used in this Roadmap as the primary term to describe active displacement. Fish migration is classified according to the life histories within fish groups, depending on their habitat requirements (freshwater *vs.* seawater) to complete their life cycle. Therefore, migration is obligatory for these fish. In this sense, three groups are considered to conceptualise fish migration [2.7]:

- Oceanodromous – migration occurs entirely within seawater boundaries.
- Potamodromous – migration occurs entirely within freshwater boundaries.
- Diadromous – migration occurs across freshwater and seawater boundaries.

Diadromous species are further subdivided into:

- Anadromous – after the first few years in freshwater, feeding and growth of later life stages (e.g., juveniles) occur in seawater. At the same time, adults migrate to freshwater to spawn, e.g., Atlantic Salmon (*Salmo salar*).
- Catadromous – after the first few years in seawater, feeding and growth of later life stages (e.g., juveniles) occur in freshwater. At the same time, adults migrate to seawater to spawn, e.g., European Eel (*Anguilla anguilla*).
- Amphidromous – most feeding, growth, and spawning occur in freshwater, but brief excursions to seawater (mainly by juveniles) can occur. E.g., Bigmouth Sleeper (*Gobiomorus dormitory*).

Natural adaptations to pristine watercourses and the life cycle requirements of each species are underlying factors shaping the movement and migration pattern. When looking into human-made regulation of watercourses (e.g., barriers created for hydropower dams) and their effect on fish migration, potamodromous and diadromous fishes are both affected in inland watercourses. Species in both groups are impacted depending on the location of a dam concerning migratory routes. For this reason, it is essential to understand the general life cycle of fish within these two migratory groups to consider their different life stages and habitat needs.

Freshwater Fish Lifecycle

Most potamodromous fish spawn multiple times during their lifetime, exhibiting external fertilization and no parental care [2.8]. Differences are observed in many diadromous species, which spawn only once during their lifetime. The spawning strategy is further differentiated by whether fish spawn in one or multiple batches. More importantly, the eggs are generally demersal (i.e., higher density than the surrounding water) and are either deposited in the water column or buried partly or fully into the substrate, where they either develop on/within the spawning substrate or freely disperse or adhere to river substrate or aquatic vegetation (adhesive eggs) [2.9]. For instance, anadromous fish, (e.g., salmon) can deposit eggs in nests (or redds). At the same time, catadromous species (e.g., eels) can have pelagic eggs that float to the surface and freely disperse [2.10][2.11].

Once fertilized, the eggs either disperse, drifting in the pelagic or surface zone or stay buried and adhered to the substrate. In both cases, the embryogenesis eventually completes and the larvae hatch. Newly hatched larvae either develop further into the river substrate or disperse to suitable habitats for growth (e.g., floodplains; estuaries), while juveniles occupy feeding sites until they reach maturity. The feeding behaviour ranges from territorial to free-ranging and schooling foraging behaviour. Once mature, adults migrate to spawning sites to reproduce. In species-rich watercourses, spawning migrations occur up and downstream in rivers, between littoral and profundal lake zones and into pelagic zones. A great gamut of literature is available for general descriptions of major potamodromous and diadromous fish groups [2.6]. A conceptual model of the expected life cycles for eels is presented in Figure 2.2.

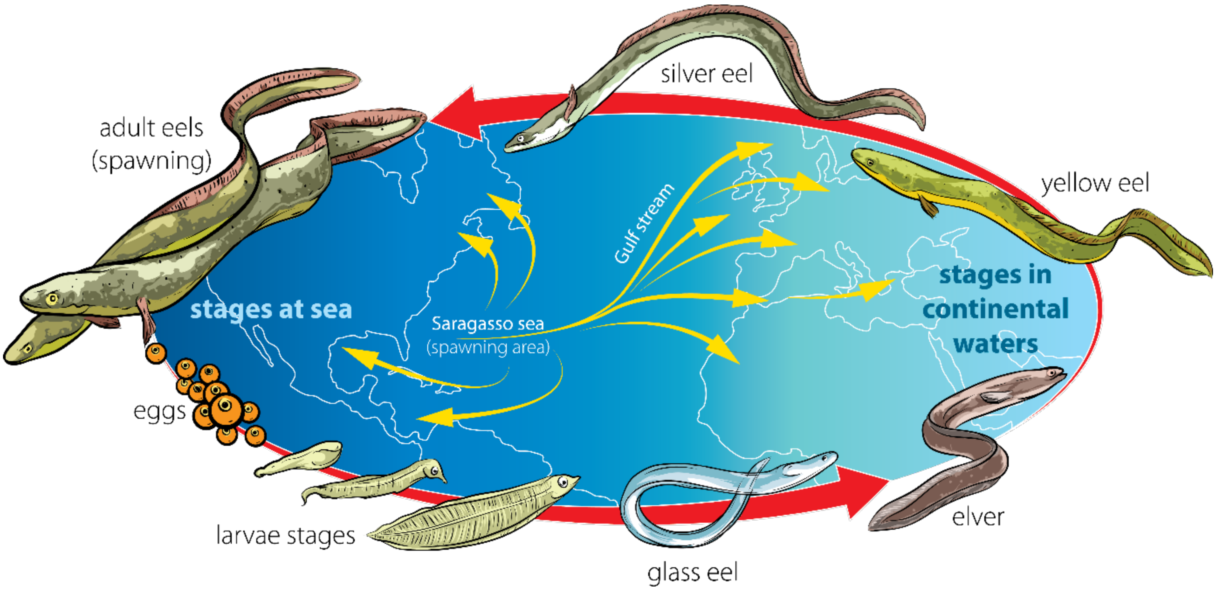

Figure 2.2 ***Lifecycle of catadromous European Eel (Anguilla anguilla)***
(Source: EreborMountain/shutterstock.com)

2.3 Awareness of Fish and Hydropower Interactions

2.3.1 ENVIRONMENTAL ASPECTS

Freshwater habitats cover only 0.01% of the planet's surface while accommodating over 100,000 species. However, freshwater ecosystems are among the most endangered ecosystems in the world. Today, only about one-third of the longest rivers in the world remain free-flowing [2.12].

HPP development creates barriers, from high-head dams to low-head diversion weirs. The barriers affect many species of aquatic organisms, from bacteria to mammals native to dammed watercourses. Fish have been chosen as target organisms to measure the impact of hydropower development due to their critical roles in both the natural and socioeconomic environments. Fish species are affected in various ways. When the development of a hydropower project creates a barrier across a river, fish can be impacted already at the construction phase. Although watercourse regulation poses similar problems to fish communities worldwide, each project presents site-specific issues and risks that must be addressed accordingly.

Each hydropower system's design, construction, and operation are unique concerning its infrastructure configurations (i.e., temporary and permanent) and how they divert water in the river channel. Therefore, understanding the design and operation of a hydropower project is vital when assessing its impacts on fish in a regulated river. HPPs induce changes in water chemistry and hydro-morphology, potentially affecting fish communities' structure and function.

There are many forms of interaction, a.k.a. challenges to address, including physical or chemical changes within the watercourse, occurring in different spatial and temporal scales due to damming and hydropower production. In Section 3, this Roadmap defines "impacts" as introduced changes to natural processes by hydropower facilities. We divide them into the following topics:

i.) Fragmentation
ii.) Impoundment
iii.) Sediment transport
iv.) Water temperature and quality
v.) Regulated flow and water abstraction

2.3.2 HISTORIC VS CONTEMPORARY HYDROPOWER DEVELOPMENT – REGULATORY SITUATION

The Roadmap covers the general essence of environmental legislative actions on a global scale; however, the ultimate solution is often simple to highlight:

Hydropower planning needs to take a holistic approach for guiding best practices for fish

First, this approach integrates all the identified and specific challenges between fish and hydropower – from i.)39 fragmentation to v.) regulated flow and water abstraction– at the watershed scale. Second, it balances solutions to achieve sustainable hydropower. It involves deciding when and where a particular facility will be built in a river basin. In many countries, the decision-making process does not consider several environmental variables, including fish, that would be affected by hydropower development at a specific site. Adopting a holistic approach at the planning phase can contribute to developing better mitigation and offset plans, or even lead to the selection of a different site for a particular HPP.

In the case of existing HPPs, the approach outlined above should be adopted when refurbishment or relicensing occurs. Ageing facilities often display other challenges with potential consequences that may have been overlooked. Common cases are listed below.

Common Case 1: Most hydropower projects have undergone a regulatory approval process before receiving a license. This would likely have included an Integrated Environmental Impact Assessment (or a similar process). The exact nature of this assessment depends on the development age (environmental law frameworks were established around the 1970s, so developments predating this may have faced a more lenient approval process) and the jurisdiction promulgating the requirements. Regulations are evolving with time, and the processes are generally more demanding and encompassing for new projects.

Potential consequence 1: *For older, existing hydropower projects, there may have been few, if any, studies on fish connectivity and ecology, and therefore baseline conditions may be unknown.*

Common Case 2: Some older hydropower projects had fish passage facilities incorporated into the design (e.g., fish ladders), which are no longer operable/operated or were not designed for all target species. The current operations personnel may be unfamiliar with the proper operation of these facilities.

Potential consequence 2: *Operations staff at older hydro plants must incorporate both original and present environmental and social requirements. The original environmental conditions (i.e., at first reservoir filling) have likely changed. It is likely, that updated studies need to be undertaken to investigate impacts and update operational protocol for fish.*

Common Case 3: Over the last decade, hydropower (i.e., reservoir and pumped storage) operational modes have changed significantly to enable system operators to accommodate the variability of other renewable sources, such as wind power and solar energy. This may have affected both the upstream inundated areas and the downstream flow regimes.

Potential consequence 3: *For many HPPs, the operating regime has changed from focusing on energy production to provide flexible services to the power grid. This may result in increased flow regulation (hydropeaking) and impacts on fish.*

The following two cases apply to both new and existing HPPs:

Common case 4: Many policymakers, particularly in industrialised nations, tend to think that the economic hydropower potential has been used up for many years. They might not be aware of hydropower's crucial role in the energy mix, which includes the provision of affordable, dependable electricity and flexible energy services to balance wind and solar production. Moreover, the economy is changing continuously, technology is advancing, and environmental, social, and economic sustainability issues are better recognised and taken into account more commonly.

Potential consequence 4: *Hydropower developers and policymakers must demonstrate a greater understanding that hydropower and fish are both necessary and mutually acceptable users of water resources. Potential conflict zones must be identified and addressed accordingly.*

Common case 5: An essential role for many hydropower reservoirs is to regulate water flows for flood control and drought management, freshwater supply, irrigation, navigation, and recreation. Water flow regulation is also becoming increasingly important to provide resilience to changing environmental conditions due to climate change.

Potential consequence 5*: When considering optimum management of fish in hydropower (e.g., reservoir management, fragmentation, connectivity, and flow releases), the needs of other water management services should be considered and ranked if necessary.*

The impacts on fish of HPPs, new or existing, large or small, reservoir-based or run-of-river, are often not fully understood nor appropriately mitigated. Therefore, it is in the hands of decision and policy-makers, operators, engineers, and ecologists to demand and implement the holistic approach and achieve sustainable hydropower development. To do so, various tools, guidelines, and protocols must be available and known to them. The Roadmap aims at filling this gap by addressing topics i.)39 to v.) with further information on specific actions. This is presented in Section 4, using a holistic approach. The Roadmap also presents simple tools to improve decision-making, which can be found in Section 5.

2.4 Sustainable Hydropower and Science-Policy interface

As mentioned, any decision involving mitigating the impacts of hydropower developments on fish must, first, meet all regulatory requirements. This section provides an overview of the general policies that need to be considered.

2.4.1 NEED FOR A DECISION-MAKING FRAMEWORK

All member states of the United Nations (UN) have adopted an agenda for sustainable development. This blueprint consists of 17 defined goals for peace and prosperity for the planet and its people. The UN Sustainable Development Goal (SDG) #6, «Ensure availability and sustainable management of water and sanitation for all» highlights the importance of water management for the planet and society. Still, rivers developed with hydropower are also touched by goal #7 «Ensure access to affordable, reliable, sustainable and modern energy for all». Also relevant is goal #15, «Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and biodiversity loss». Since it is essential to life, water can easily be connected to almost all SDGs.

Likewise, hydropower and fish are embedded into all three dimensions of sustainability (i.e., social, economic, and environmental) and can be connected to various policies. Major policies of international importance are *Climate* and *Energy Policies* and, more recently, *Biodiversity*. It is not always easy to navigate these complex policies. Still, renewable energy and environmental protection policies can support each other and deliver essential synergies if managed correctly. The topic of hydropower and fish is embedded in the different spheres of the total environment: in the biosphere (e.g., fish, biodiversity), the anthroposphere (e.g., energy, navigation), the atmosphere (e.g., climate), the lithosphere (e.g., sediments) and the hydrosphere (e.g., river flow, hydropeaking) [2.13]. The need for more sustainable hydropower under changing policy frameworks and market conditions is interlinked with the different spheres of the total environment and the three dimensions of sustainability. For example, sustainable hydropower must provide a more flexible energy supply and minimize negative impacts on aquatic ecology, including fish.

The aforementioned holistic approach, also known as integrated river basin management, is critical to address the challenge of balancing the sustainable use of water resources to protect those vital ecosystems. National and cross-border River Basin Management (RBM) policies are essential to integrate and balance environmental spheres, the multipurpose uses of rivers, and energy. Forward-looking strategic planning, multidisciplinary research, and innovation are essential drivers for future sustainable policy and decision frameworks. Any decision-making framework would have to respond effectively to the main policy drivers. It would also need to account for regional particularities, in terms of the national energy system, the river system, and the fish population, for example [2.13].

Although ecological considerations need to be part of hydropower operation and management, it can be challenging to optimize economic and technical hydropower operation and minimize adverse effects on fish simultaneously; an example of this is during hydropeaking (See Section 4.6.3). International information sharing and cooperation in research will be an essential step for achieving a common understanding of the objectives of the decision-making framework, which can be generalized in best practices. To ensure the framework's relevance, it will need to differentiate between factors that are important across the board and factors that are important but applicable only in certain local areas.

This process is fundamental to the comparative analysis of different river systems concerning hydropower, fish, and ecosystem characteristics. In this context, monitoring and reporting, as required by local legislation, can be an essential tool in consolidating information on river systems in the context of hydropower and fish, going beyond fish ecology *per se*, e.g., the Clean Water Act [2.14] in the United States of America, or the Water Framework Directive (WFD) in the European Union (2000/60/EC)[2.15]. Guidance documents for applying an integrated and strategic planning approach to hydropower exist, and implementation offers an excellent opportunity to integrate water, nature, and energy policy objectives on any scale from local to the country and international levels [2.16].

2.4.2 RECOMMENDATION FOR REGIONS AND COUNTRIES WITH LITTLE OR NO REGULATIONS FOR SUSTAINABLE HYDROPOWER DEVELOPMENT

In some regions, national regulations and environmental policies for hydropower do not account for the sustainable development of hydropower technology. There is a risk in such cases that hydropower investors, particularly private or foreign investors and shareholders, in combination with unqualified regulatory agencies, use outdated national regulations and do not voluntarily adopt internationally recognized standards (from the World Bank, International Hydropower Association (IHA), among other standards). Then, upon hydropower operation, the hydropower owners or operators risk conflicts with NGOs or poor social acceptance of the project. This may lead to more expensive measures than if environmental priorities had been properly addressed at the designing stage.

2.4.3 PRESENTED MODEL: EUROPEAN POLICIES

This section outlines the interplay between different legislations and policy packages using the example of the European Union. Naturally, from this follows a necessary interplay of policies and derived legislation responding to those policies.

As one of the largest renewable electricity sources worldwide and in Europe, hydropower is a significant contributor under the Renewable Energy Directive [2.17] and the EU Climate and Energy Goals for 2020 and 2030. It is also in line with the Paris Agreement [2.18]. However, like any other industrial activity that impacts the environment, hydropower must conform to the requirements of EU environmental law. Legal requirements for the protection and restoration of rivers and lakes in Europe are established by the EU WFD, the Floods Directive [2.19], the Birds and Habitats Directives [2.20], and the Environmental Assessments Directives (Environmental Impact Assessment – EIA [2.21] and Strategic Environmental Assessment – SEA Directives [2.22]).

In particular, the WFD, adopted in 2000, is an essential legislative framework in the EU that promotes a more holistic approach to water policy at the river basin scale. It aims at ensuring that all water bodies meet “Good Ecological Status” (GES) within a specific deadline. Heavily modified water bodies need to meet “Good Ecological Potential” (GEP) by implementing ecologically efficient mitigation measures. The definition of “good ecological status” reflects the overall health of aquatic ecosystems, including floodplains. It includes macroinvertebrates, macrophytes, diatoms, and fish fauna with their habitats and objectives to restore river continuity. Notably, the WFD goes beyond the essential requirement of preventing the further deterioration of water bodies and aims at improving them. To achieve these objectives, EU Member States should establish a monitoring program to assess the state of all water bodies and establish RBM plans for each river basin district, including management objectives and measures. These RBM plans, and information on the status of water bodies, are reported every six years to the European Commission, which then publishes assessment reports (e.g., Fitness Check of the Water Framework Directive [2.23]). The recent evaluation of the WFD shows that hydropower exerts significant pressure (direct environmental effects from different drivers, like climate change, agriculture, and urban development) on aquatic ecosystems in the EU. To address this, the WFD includes specific requirements to ensure that the impacts of certain activities, including hydropower, are mitigated as much as possible with relevant measures without significantly affecting their use – Article 4(3) of the WFD. This means that new hydropower projects must meet specific requirements. The expected impacts of the projects should be assessed. If there is a possibility of ecological damage, the project can only be approved by the relevant authorities if certain restrictions are met, as described in Article 4(7) of the WFD. Meeting those conditions requires proper integration of the water and energy policies, including environmental considerations, at the early stages of the energy planning process.

While the WFD covers all surface waters in the EU and EEA-territory (including Iceland and Norway, which are major HPP countries), the biodiversity policy of the EU complements it by addressing certain types of species, habitats, or pressures. The Birds and Habitats Directives (Nature Directives) is an essential legislative element of the EU's biodiversity policy to conserve the most endangered species and habitats within the EU member countries. Atlantic salmon and European eels are one of the most known red-list species protected by the Habitat directive. Both directives aim to maintain and restore a favourable conservation status and protect the species and habitat types. To achieve this, a network of protected areas called Natura 2000 [2.24] covers over 18% of the EU's land area and more than 8% of its marine territory. Specific legislation also aims at protecting specifically migratory fish. In particular, the Eel regulation aims to protect and restore the Eel population by addressing all pressure threatening its survival, including the deterioration of its habitat and migration corridors [2.25]. A Pan-European action plan for sturgeons was also adopted in 2018 to conserve the last surviving sturgeon populations [2.26]. Another highly relevant measure, the Invasive Alien Species Regulation, aims to address the spread of invasive species threatening native biodiversity in Europe [2.27].

In response to the alarming loss of biodiversity in Europe, the European Commission recently launched a new biodiversity strategy for 2030, setting objectives to reverse biodiversity loss. This strategy includes specific objectives for the freshwater ecosystem, aiming at restoring river continuity by stepping up the implementation of the WFD. This involves the restoration of at least 25,000 km of rivers into free-flowing streams and the implementation of environmental flows.

Climate change poses additional threats to aquatic ecosystems. The WFD and the Floods Directive (2007/60/EC) are key instruments to address it. Member States should identify 'significant pressures' affecting water bodies and incorporate appropriate measures in their planning process.

As part of the adopted EU taxonomy of sustainable finance, several fish-relevant mitigation measures and their ecological effects are specified to meet the requirement for sustainable electricity from hydropower. This includes sustainable solutions for safe dam passage for migratory fish, environmental flows, hydropeaking mitigation, and mobilising flows for sediments for both new and existing HPP. The expected level of mitigation from these solutions also needs to be documented by adequate monitoring, and if necessary through adaptive management. This applies also to the investments of European actors in other continents.

Mitigation, Conservation, and Restoration Targets

The European WFD is an excellent example of ecosystem-based river basin management to link measures and ecological effectiveness by establishing *Good Ecological Status* or *Potential* (GES and GEP, respectively). This directive has an international reach and drives hydropower development towards sustainable goals in Europe [2.13]. The ecological status of surface waters is assessed according to the following criteria to ensure the best approximation to the ecological continuum in river basins:

- Biological quality (e.g., fish, benthic invertebrates, aquatic flora).
- Hydro-morphological quality (e.g., riverbank structure, channel continuity, substrate attributes, environmental flows).

- Physicochemical quality (e.g., temperature, oxygen, nutrients).
- GES and GEP are defined by intercalibrated thresholds that need to be exceeded by indicator organisms and by chemical and hydro-morphological indicators in each category.

Some procedures for identifying the physical quality of a given body of water vary among the Member States. An inter-calibration mechanism is in place to assure comparability of the values provided by the various member states [2.15]. The assessment is complex and evidence-based, but it remains impractical for some purposes, such as setting quantitative mitigation targets for specific hydropower locations or elaborating global standards.

Further information on environmental legislation in the context of hydropower is available in the corresponding guidance document of the European Commission [2.16].

2.4.4 PRESENTED MODEL: HYDROPOWER SUSTAINABILITY TOOLS

The hydropower sector has developed a set of sustainability tools that can be applied to assess the sustainability of hydropower projects. The Hydropower Sustainability Assessment Protocol (HSAP) can be used to assess the sustainability of projects in all their phases: planning, construction, and operation. The HSAP was developed between 2007 and 2010, following a review of the World Commission on Dams' recommendations, the Equator Principles, the World Bank Safeguard Policies and IFC Performance Standards, and IHA's previous sustainability tools. During this period, a multi-stakeholder forum jointly reviewed, enhanced and built consensus on what a sustainable project should look like. This forum included representatives of environmental and social NGOs, development banks, governments, and the hydropower sector.

The HSAP is built around the three basic sustainability pillars: environmental, social, and economic sustainability, and covers the full breadth of sustainability issues related to hydropower projects. Some of the topics are unique for each of the project phases. In contrast, others are relevant in all project stages, such as *Environmental and social assessment and management*, *Infrastructure safety*, *Financial viability*, *Indigenous people*, *Cultural heritage* and *Biodiversity and invasive species*. An independent and certified assessment of a project's sustainability can be obtained through certified assessors. At the same time, the tool can also be used internally by companies as a systematic approach to improve sustainability performance. The scoring of each of the topics ranges from 1 at the low end to 5 at the top, indicating a proven best practice in the industry. To qualify for the highest score, the topic (e.g., regulated flow regime downstream) must be thoroughly assessed and aligned with all relevant legislation. It also needs to have been extensively communicated with stakeholders and gained support.

The Hydropower Sustainability ESG Gap Analysis Tool (HESG) enables hydropower project proponents and investors to identify and address gaps against good international practice. The HESG is a less comprehensive tool based on the framework of the HSAP. It assesses projects against the requirements of the HSAP's environmental, social, and governance topics. It gives as an output an action plan to help project teams address any gaps in good practice.

2.5 Impact Assessment and its Role in Determining Hydropower Effects on Fish

The Impact Assessment and its Goals

The adoption of the Environmental Impact Assessment (EIA) to investigate the potential impacts of economic activities on the environment has achieved a global reach after the first United Nations Conference on the Human Environment in 1972. The requirements for EIA studies are set in the legislation and policies of different countries and by international funding organizations such as The World Bank. These studies are paramount in defining the type, magnitude, probability of occurrence, and significance of an environmental impact, as well as other parameters. Most importantly, the EIA is relevant in contributing to a new decision-making process of the project, including the design of mitigation measures.

One general issue related to quantifying the magnitude or severity of impacts is that the assessment is based on expert knowledge. Therefore, quantitative targets should be considered to assess the magnitude of the predicted impacts of a hydropower project on the fish fauna. For instance, if assessing the impacts of a project on migratory fish, the EIA should be based on data about the diversity and abundance of migratory species observed in the affected area, the spatial distribution of critical habitats (e.g., spawning and rearing habitats) for those species (upstream and downstream of the future dam), recruitment, and dispersion distances amongst other variables.

In the context of hydropower, the requirements of the EIA can vary significantly between countries and according to data availability and project type. For the latter, the size of the project will generally be the leading factor in determining what studies are needed. Small HPPs usually have different requirements for EIA studies than large HPPs. More importantly, the timeline for EIAs can differ significantly between countries. Sometimes, the EIA takes place after a project has been designed and the economic feasibility defined, leaving little space for design adaptation and planning for mitigation alternatives [2.28]. The design of mitigation measures will be much more effective if incorporated into the dam design since this makes it possible to assess the cost-effectiveness of different options.

Fish Passages as Examples

Fishways, for example, would benefit greatly from a comprehensive EIA to support decision-making processes related to mitigation measures for HPPs. For new and existing HPPs, the design of effective fishways is directly related to the ecological targets set for that mitigation measure. The EIA should serve as a baseline to set those targets based on the fish community structure identified in the area that will be or is already affected by a hydropower dam. Ideally, the decision-making process for a fishway (see Section 5) should follow a structured framework and be present at the early stages of the dam design. However, depending on the legal requirements for the implementation of the EIA, the information obtained with the impact assessment may be limited, or the decisions about mitigation options and management plans may come late in the process.

To exemplify this, Figure 2.3 present an overview of the stages within the legal framework to develop a small HPP in Brazil [2.28]. Schematics of the decision-making process illustrate the different stages (numbers 1 to 5) and relevant actions related to each. Based on the framework presented, the design of a fishway would be detailed after 'Stage 4 – Project Approved' which often creates various issues based on the following:

- Disconnection of the EIA from the development of the mitigation plan.

- Financial constraints since the final design and detailed project are finalized before developing the Environmental Management Plan (EMP), including the mitigation options.

- Dam construction has already started at this stage, and complementary information is generally obtained with environmental alterations.

These issues, associated with other legal requirements for the construction of fishways, can lead to ineffective structures for fish passage [2.29] or to scenarios where they may function as ecological traps [2.30]. In these scenarios, a rapid change in environmental conditions may lead species to adapt to poor-quality habitats.

To summarise, the EIA progress must be included in the early stages of the dam design. The outcomes of the EIA should serve as the basis for the development and implementation of the EMP, including the mitigation and conservation targets and selection of relevant monitoring technologies.

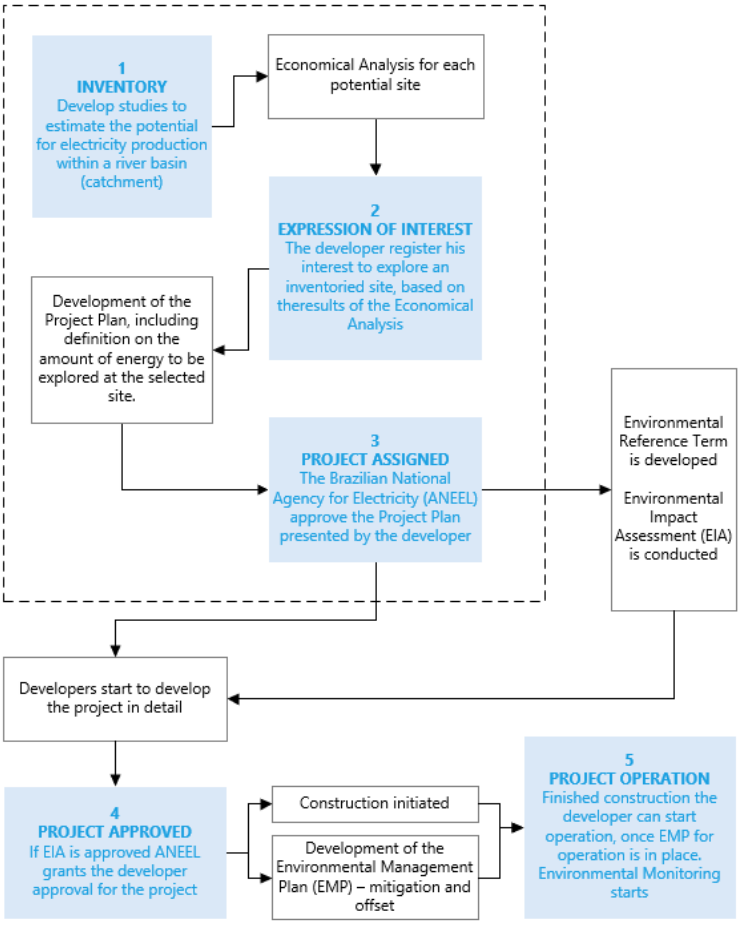

Figure 2.3 ***Schematics of the decision-making process for small hydropower plants in Brazil*** (Redrawn from: [2.28]).

2.6 Set of Ecological Aims: Mitigation and Conservation Targets

Fish and their life stage-dependent habitats are commonly used as indicators of ecosystem health when assessing habitat suitability metrics, upstream and downstream passage, or other ecological aspects. They are often supplemented by expert opinion, traditional knowledge, and more holistic aspects [2.31][2.32]. Therefore, this section will cover a set of ecological aims based on mitigation, conservation, or restoration targets, which are also commonly targeted by different policies.

Hydropower affects aquatic organisms through hydrologic, morphological, hydraulic, thermal, and physicochemical changes to their habitats and impairs organisms' movements. In general, these impacts can lead to ecological shifts, reduced biodiversity, changes in aquatic community structures, and loss of species [2.33][2.34][2.35]. Implementing effective mitigation and conservation measures to address hydropower impacts requires a set of adaptable ecological aims specific to various ecoregions around the globe. Based on suitable habitats to support aquatic life, a global framework offers scientifically defensible metrics to balance power generation and ecological, social, and economic aims.

Ecological Aims

A goal for mitigation, restoration, and conservation is to ensure access and abundance of suitable habitats for organisms in an ecosystem. A set of ecological aims for effective mitigation and conservation measures in hydropower-impacted bodies include the following elements:

1. **The extent of the affected area**: when re-establishing connectivity, measures will differ if the aim is to protect habitats upstream or downstream or if the affected area has a single or cascade of dams.
2. **Fish diversity**: do mitigation goals apply to the fish community or a subset of species? It may be challenging or unsuitable for defining a set of target species, especially in megadiverse areas (with more than a hundred native fish species); in such cases, functional or habitat use groups (guilds) may contribute to set intervention goals.
3. **Identify anticipated habitat structure** (i.e., proportions of suitable area) for different species or habitat use groups.
4. **Social and economic importance of species** in the affected area, including consideration of invasive species, where they are present.
5. **Information on new and existing HPPs** in the affected area with highlights on the potential of cumulative or synergistic impacts from multiple dams.

Such elements can be defined based on a list of anticipated, protected, particularly concerned, or indicator species. One or multiple indicator species are usually chosen as representative species of a river section or habitat or as the most threatened by habitat alterations. Indicator species need to be sensitive to human-induced alteration to be of value for mitigation, restoration, and conservation plans. Alteration of fish community structure can be measured with an affinity index (i.e., similarity), which observes a shift of proportions of species from expected fish communities. This fish community structure is a function of habitat structure. Therefore, this index may be applied to the habitat structures as well.

Further information on species is available via other sources. For example, status reports on threatened species are available through the International Union for the Conservation of Nature (IUCN) databases. They provide information on the main threats to each of the evaluated species, which in the case of Europe are related to dams and water resource management. A report from Brazil is also available with the aim to assess the ecological conditions or status of catchment alterations by hydropower plants [2.36].

To determine ecological aims for sustainable hydropower, quantitative data on fish communities are best, preferably for pre-impoundment conditions (i.e., baseline reference). However, these are rarely available where monitoring programs are not in place, particularly in mega-diverse areas. The existence of policies and guidance from Europe, North America, South Africa, and Australia can inform other world regions and contribute to effective mitigation and conservation measures even with limited available data [2.31]. Such legislative and policy instruments include for example:

- The Water Framework Directive and the Taxonomy of Sustainable activities, European Union [2.15].
- The Endangered Species Act, U.S.A. [2.37].
- The Fisheries Act, Canada [2.38].
- The Environmental Protection and Biodiversity Conservation Act (EPBC), Australia [2.39].

They provide similar ecological aims and ways to meet the challenges and encourage research and development to fill knowledge gaps.

Contribution of Research and Innovation to Mitigation, Conservation, and Restoration Targets in the European Union

Under the European Commission Horizon 2020 Framework Programme for Research & Innovation, a series of initiatives were funded to assess hydropower impacts on European fish populations. They influenced the definition of parameters to define hydropower sustainability. The Fish-friendly Innovative Technologies for Hydropower (FIThydro) and the Adaptive Management of Barriers in European Rivers (AMBER) are examples of initiatives that contributed to setting ecological aims for mitigation, conservation, and restoration of fish in hydropower-regulated areas.

One of the AMBER project products is a European map of locations of expected fish community habitat structures. These structures are modelled from Pan-European fish observations related to geographical settings such as altitude, climate, or geology at fishing locations. In this model, fish are divided into groups of species using similar habitats, so-called habitat use guilds. Examples of maps covering fish community habitat structures may be found on the AMBER website and in its associated deliverables [2.40]. The habitat structure at the site can be determined using a habitat simulation model during the planning process. Ecological target conditions for current or simulated future habitat structures can be compared. An affinity index checks how far the current or planned conditions differ.

The FIThydro project developed several guidelines and valuable tools for the practical assessment, mitigation, and conservation of hydropower projects. These are shown on the FIThydro wiki.

In addition, relevant articles on sustainable hydropower practices are published in *Hydrobiologia 2020* [2.41], as well as compiled in [2.42].

SECTION 3. HYDROPOWER AND FISH: COMPETING INTERESTS

Section 3 identifies the most significant challenges regarding issues (defined as a challenge which will occur) and risks (defined as a challenge which may occur) arising from the interactions of hydropower development and its operation with fish communities.

The section starts with a description of the functionality of hydropower and then focuses on the resulting alterations to watercourses. These alterations are classified as morphological, physicochemical, and flow quantity. In each case, the impacts on aquatic life are discussed. Risks mainly focus on freshwater habitats and their availability to fish.

Having identified the impacts of any specific hydropower development, the reader is then directed to Section 4, where possible options to manage the issues and risks are discussed. Section 5 summarizes decision-making methods to help determine appropriate mitigation for further consideration, and Section 6 covers monitoring to gauge effectiveness.

3.1 Hydropower Functionality

Hydropower developments are based on creating a barrier to retain and regulate flows in a natural river to provide hydraulic heads and regulated flows for electrical generation. This is usually achieved by the diversion and/or storage of water by structures such as dams, weirs, and canals, being very diverse in terms of size and type of hydropower plant, size of generating unit, hydraulic head, and overall function (i.e., energy, power, or multi-purpose). Hydropower facilities can also be installed at existing barriers not originally built for energy production. The structures are site-specific and dependent on local conditions. For example, many barriers are associated with hydropower plants, subdivided into dams retaining a reservoir and headworks diverting flows through tunnels, canals, or conduits.

In any configuration, waterflows are passed through designated outlets that form part of the hydropower facilities. Power flows pass through intakes, water passages, and turbines before being discharged through the draft tubes. When inflows exceed the rated discharge capacity of the power units, these excess flows are either retained by the reservoir or spilled. In well-managed hydropower facilities with storing capacity, the spilling of excess flows is kept to a minimum (i.e., compensation flow, best managed by retention in the reservoir). In the infrequent occurrence of a flood greater than the retention ability, flood water passes over spillways or through other discharge facilities.

Flows are discharged either from the powerplant or from other discharge facilities. When flow is released through the powerplant, it forms the tailrace. In contrast, flows discharged from the spillway or other discharge facilities form the plunge pool or other energy dissipaters like stilling basins. Flows from the tailrace and plunge pool are collected in the tailrace channel, which joins the original river channel. However, in some developments, the powerplant is located at some distance downstream of the diversion structures on the river. It may even be constructed in an underground cavern with discharge through tailrace tunnels.

Ecologically relevant interrelationships are described in Section 3.2 with further details. They include impoundment of a river stretch, changes in the sedimentation process and water quality, and spatial and temporal flow regulation, among others.

Classification of Hydropower Plants

Hydropower plants are often classified according to various criteria. It can be according to the size, head, capacity of production, typology, way of exploitation, purpose, location of the powerhouse and operation mode, and whether they are integrated into the transmission system. A general overview of the various classification system is presented in Figure 3.1.

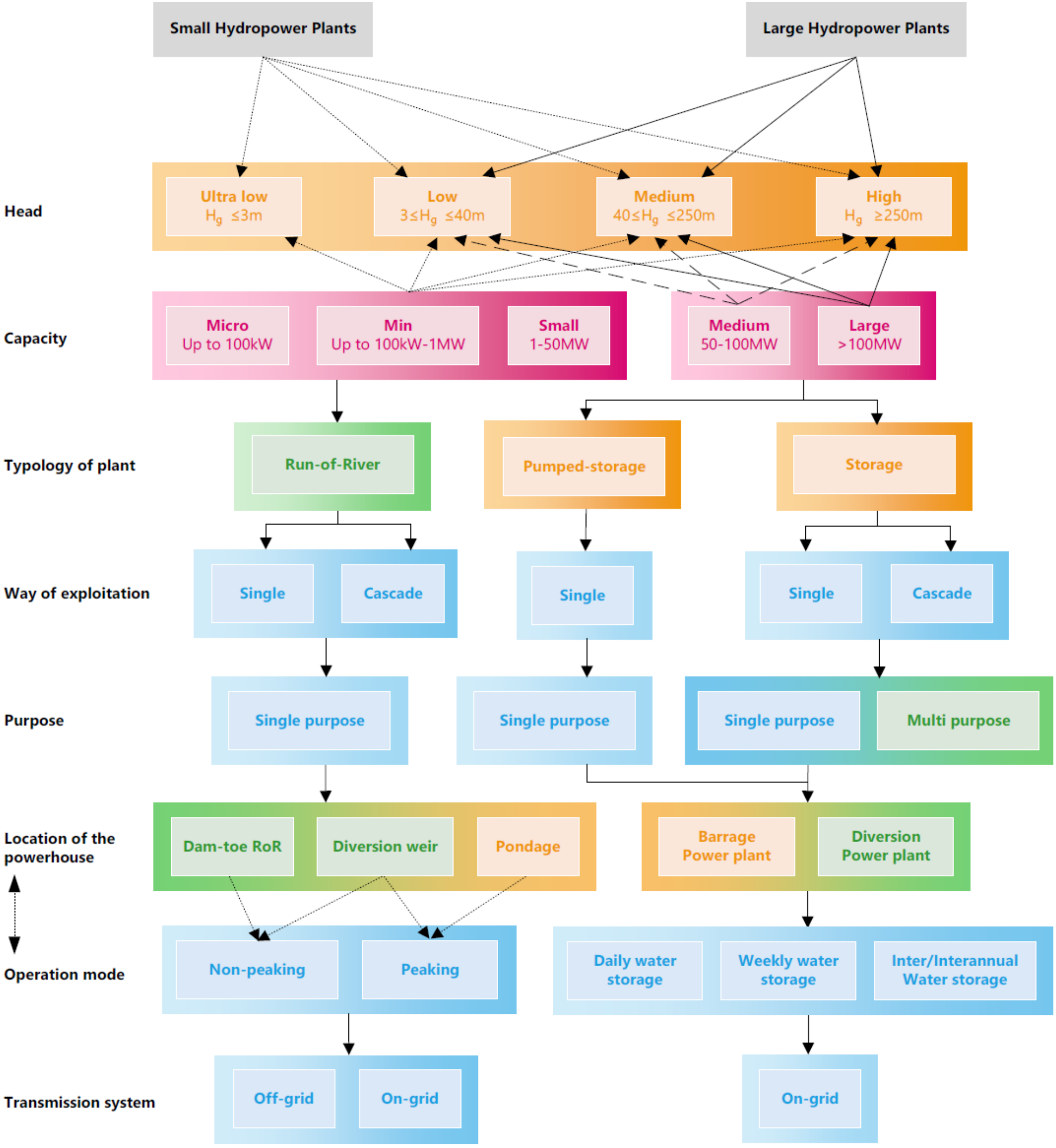

Figure 3.1 ***Classification of hydropower plants according to different criteria*** (Source: [3.1])

This roadmap classifies hydropower plants (HPPs) into three functional categories according to the typology of the plant: run-of-river (RoR), storage (or reservoir) HPP, and pumped storage plants (PSP). RoR and storage HPP can be combined in cascading river systems. PSP can utilize the water storage of one or several storage HPPs.

Run-of-River (RoR)

Run-of-River hydropower schemes harness energy mainly from available river flows (Figure 3.2). They are commonly considered to have limited storage and some jurisdictions limit this to 24 hours. For this Roadmap, RoR plants will be considered as holding no storage. Electricity generation is driven mainly by natural river flow conditions or releases from upstream storages. Power generation is primarily a function of precipitation and runoff and therefore has significant seasonal variability. For a maximum value of power generation or for simultaneously serving multiple purposes within the river catchment, coordinated management is required among the reservoirs and their operators, especially in cases where upstream reservoirs have different owners than the RoR facility downstream.

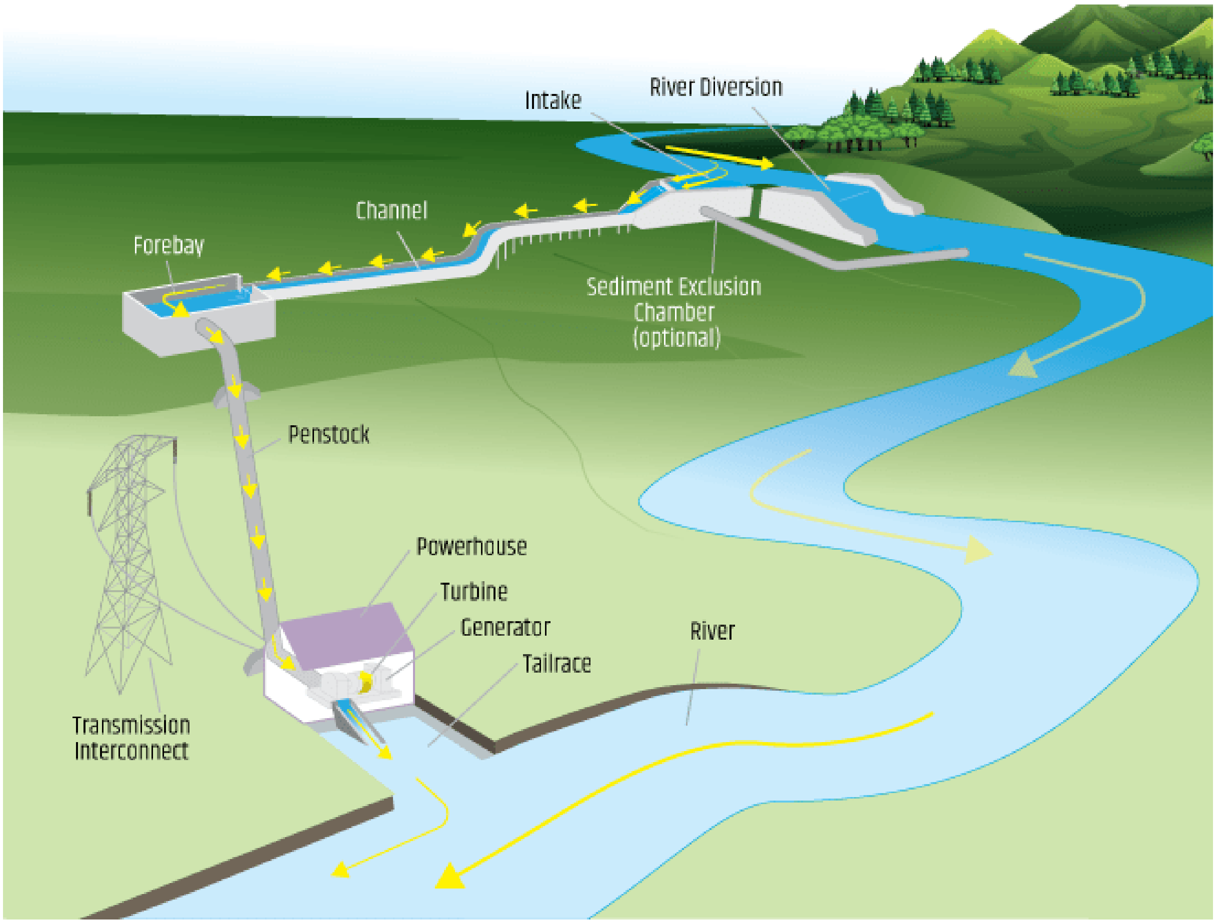

Figure 3.2 ***Run-of-river (Diversion) type of hydropower plant*** (Source: U.S. DoE)

Reservoir Storage (storage HPP)

Most reservoirs of HPP are developed by impounding natural river flow behind a dam (Figure 3.3). However, some are formed by rising a natural lake. The powerhouse is either located by the dam toe or further away from the dam. The stored water provides the flexibility to generate electricity as required by the electrical system while reducing the variability of inflows. Vast reservoirs can store months or even years of average inflows (stored energy). They can also provide other multi-purpose services (see IEA Hydro Annex IX), for instance, flood and drought protection and irrigation services. Most reservoir hydropower schemes generally serve various purposes, depending on the region’s environment and social needs.

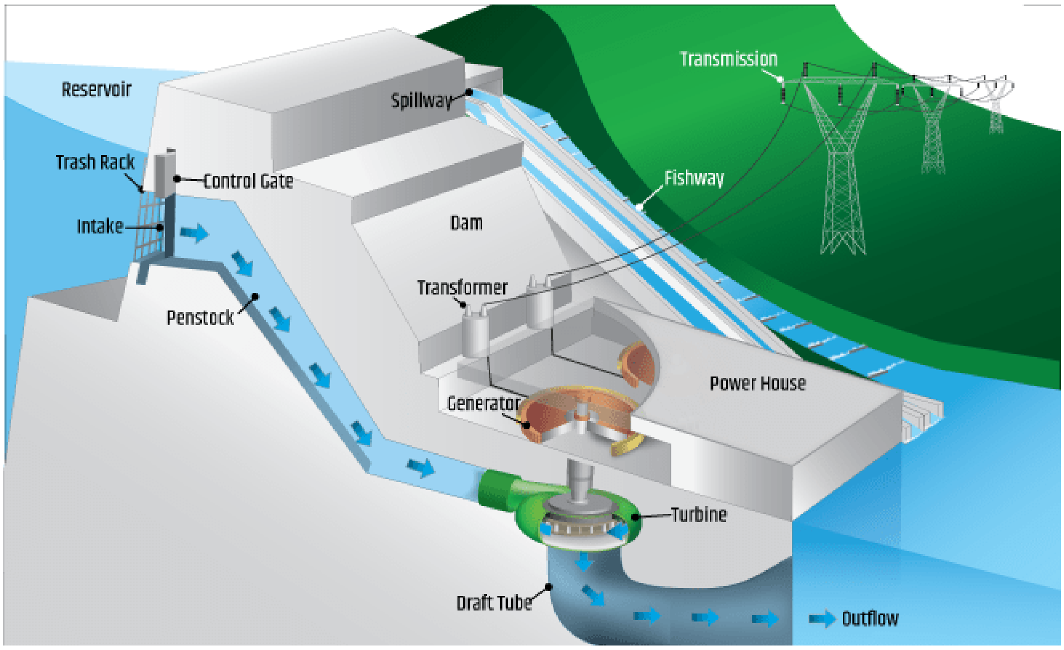

Figure 3.3 ***Illustration of reservoir storage hydropower plant (Storage HPP)*** (Source: U.S. DoE)

Pumped Storage Plant (PSP)

PSP pumps water from a lower reservoir to an upper reservoir (Figure 3.4). When conditions dictate, it reverses the flow direction and generates electricity. They were first built to balance the difference in electricity consumption and generation capacity at thermal-based power systems. The mode of operation is driven by electricity market signals, mainly electricity supply levels and prices. This is increasingly dependent on the regional penetration of other renewable energy sources, such as wind and solar power.

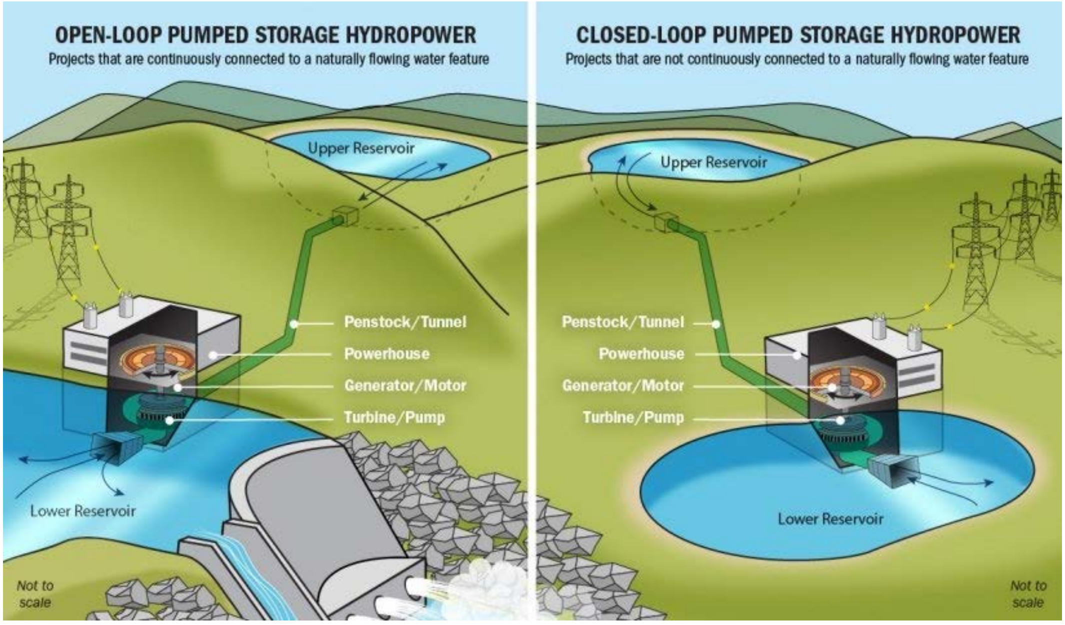

Figure 3.4 ***Open vs closed pumped storage hydropower scheme*** (Source: U.S. DoE)

While PSP is a net electricity consumer (i.e., an efficiency of 70 to 80%), it is a significant energy storage provider. Many PSPs are “open-loop” systems developed from an existing HPP system by adding either an upper or a lower reservoir. An open-loop PSP may even be built in higher altitudes between two existing HPP systems. They are usually “off-stream,” consisting of a lower reservoir on a stream, river, or other watercourse and a reservoir located off-stream, usually at a higher elevation. Closed-loop systems are independent of existing water streams; both reservoirs are off-stream [3.2].

Operational Strategy of Hydropower Plants

The operational strategy of an HPP, while being project-specific, has a regime based primarily on facility configuration, license constraints, and electricity market requirements. In general, HPPs have historically been designed, managed, and operated primarily to provide safe and reliable energy generation and energy services at minimum cost on a sustainable basis.

Operational safety is ensured by routing extreme flood events past the dam with minimal damage and acceptable downstream impacts. This is normally achieved by providing adequate storage capacity in the reservoir and appropriately sized discharge facilities.

Reliability covers the operation of the generating facilities and the water resource to ensure that energy generation is maintained. This normally involves drawing down the reservoir level to capture seasonal variations in inflows and storing enough water to manage periods of drought.

With the increasing deployment of variable renewable energy (VRE) sources (wind and solar energies), hydropower operations in many jurisdictions have changed. These changes have significantly affected the role of hydropower and, consequently, its impact on fish [3.3]. The requirement to balance VRE sources has provided hydropower with both an opportunity and the requirement to deliver these essential services and maintain system quality criteria. The provision of flexible services from hydropower plants requires that flows through the turbines vary depending on operational modes. In some cases, this can be a “continuous change” when undergoing load following; in others, it can be a start-up and shutdown of units at peak times. As HPPs and PSPs are low-cost sources of flexibility, they often provide these services in support of energy systems to help balance wind power and solar energy variability on regional and continental levels.

Additionally, hydropower facilities provide further water management services, especially those with storage reservoirs. These include water supply, irrigation, flood control, navigation, and recreation. Alongside these benefits, there can be challenges to the ecosystem, such as ponding natural watercourses, preventing fish migration, and reducing water quality in the reservoir and downstream.

3.2 Hydropower-induced Changes to Watercourses and their Impact on Aquatic Life

Hydropower facilities hinder the continuity of watercourses for fish, flow and sediment and hence natural processes. Hydropower-induced changes to watercourses include:

i.) Fragmentation

ii.) Impoundment

iii.) Sediment transport

iv.) Water temperature and quality

v.) Regulated flow and water abstraction

These changes can affect fish communities directly (i.e., mortality from HPP turbine passage, stranding or fish must pass through artificial structures during migration at fragmented river sections) and indirectly (i.e., through changes in habitat abundance and quality) [3.4][3.5]. The effects on habitats are variable and dependent on the type of dam, the project footprint, and site-level characteristics, including the design of the hydropower scheme and operational mode. Further, the interruption of biota movement by fragmentation has broad ecological and conservation consequences, ultimately affecting gene flow and population dynamics [3.6][3.7]. Overall, such changes may favour generalist species (which tolerate a wide variety of environmental conditions, including decreased water quality conditions) by reducing the availability of complex habitat characteristics (i.e., with spatially varying velocity, flow, and temperature conditions)[3.8].

It should also be noted that not all hydropower projects are associated with the challenges mentioned above. Moreover, different hydropower facilities may involve various processes, posing different issues and risks for fish. While both RoR and storage HPPs have barriers and structures that impede the free passage of fish, in the case of PSPs, it is assumed that there is no fish migration between the upper and lower reservoirs of pumped storage hydro (i.e., there are cases where a pumped storage hydro scheme is combined with HPP with storage; such hybrid schemes will be treated as storage HPP in the Roadmap). In addition to migration barriers, other issues associated with storage hydro include changes in flood regimes and other processes that would naturally provide aquatic habitat both upstream and downstream. The main processes and their common associations with hydropower types are discussed below, following the challenges from i.)39 to v.) regulated flow and water abstraction. It shall be noted that challenges often result from complex interrelationships and synergies, and thus are not related to a single process alone. For clarity, the Roadmap introduces the challenges with the process, which it is mostly associated with.

3.2.1 FRAGMENTATION

Most fish species display migration behaviour during their life cycle, short or long distance, once or multiple times. Migration is an evolutionary strategy based on exploiting different habitats for feeding, growth, spawning, or survival at different times of the year and as part of a lifecycle. Such migration can be crucial to sustaining fish populations adapted to the environment where they have lived for thousands of years.

The degree of longitudinal and lateral connectivity in dammed rivers greatly influences habitats and species assemblages. Fragmentation is the term used to describe the impact of artificial structures, like dams built for electricity production that:

A. affect the passage of migratory fish and limit their range and/or abundance, and

B. substantially change the natural habitat distribution within rivers and modify their ecological carrying capacity.

It thus describes the difference between the natural range and the actual range of migratory fish in river systems due to artificial obstacles and habitat changes. Note that barriers, like dams, may not always be associated with hydropower development. At the same time, the impact of alike artificial structures would be similar.

Changes to the physical environment, such as those caused by hydropower structures, might hinder the fish’s ability to maintain their population size. Dams generally impede or completely block river channels and limit the free movement of native fish species between upstream and downstream sections. Dams may prevent fish from reaching essential habitats such as breeding grounds or thermal refuges. In numerous cases, this leads to the destruction or reduced abundance of species (i.e., especially concerning diadromous and potamodromous fish) depending on the level of connectivity which is also determined by the efficiency of applied mitigation measures.

Each dam presents unique cases that must be considered when assessing impacts and developing mitigation measures. While hydropower has many benefits as a major renewable energy source, it changes and affects the natural processes in rivers and water bodies. However, some hydropower projects have environmental and social challenges due to their potential impact on fish migration and species composition. Thus, knowledge gained from case studies, technology choices, mitigation options, and sustainability goals for fish habitat provisioning and maintenance are important ways to reduce the potential impact of fragmentation.

Flow Conditions at the Turbine and the Tailrace

Fish passing through the turbine are at high risk of injury or mortality due to direct striking by the turbine blades, barotrauma (fish injuries due to sudden changes in pressure [3.9]), high shear stresses, turbulence intensities, and cavitation. Out of these, mechanical injury mechanisms and barotrauma are considered dominant. The edge blade strike is assumed to be the primary cause of fish mortality due to turbine passage [3.10]. Furthermore, turbine passage causes unfavourable conditions for fish survival in the tailwaters, such as disorientation and potentially increasing mortality related to aquatic and avian predation.

Hydraulic conditions in the tailrace are a direct consequence of the dam and powerhouse layout and the operation of the power and spill facilities. Most developments were designed to maximize energy production and pass excess flows safely. In some cases, this may attract fish away from appropriate passage routes. Therefore, many hydropower projects can cause a significant delay in the upstream migration of fish or divert them from fish passage facilities such as the entrance to fish ladders. It is a risk on rivers where migratory species with strong swimming capabilities are present (e.g., Atlantic salmon (*Salmo salar*) or Brown trout (*Salmo trutta*)). The turbulent flow in the tailrace attracts migrants into draft tubes, where they may come in contact with structures or turbine runners or be exposed to hydrodynamic shear forces or abrupt pressure changes. Such encounters can cause severe or lethal injuries unless the turbine chamber and flow passages are designed for (ecologically) improved conditions for two-way fish passage.

Issues associated with fragmentation:

- Barriers impede the free passage of fish to migrate and limit their range and/or abundance.
- Substantial changes caused by barriers affect the natural habitat distribution of fish within rivers, which modifies their ecological capacity.

Risks associated with fragmentation:

- It may partially or completely block the movement of fish past a dam in one or both directions.
- Fish passage facilities may only be adequate for a limited number of fish species or only in the passage in one direction (upstream or downstream).
- Tailrace flows may attract upstream migratory fish away from fish passage facilities.

3.2.2 IMPOUNDMENT

Physical changes to the naturally free-flowing environment following the fragmentation of a river by a dam are inevitable (Figure 3.5). This process transforms the riverine environment from lotic (flowing water) to lentic (still water) conditions. The process is important for the species assemblages in the impounded (inundated) area. Changes in fish communities are commonly observable through the dominance of planktivorous and generalist fish species, as they usually benefit from a lentic environment. Furthermore, impounding a watercourse also increases the risk of exotic fish infestation, impacting the affected region's food web structure. For migratory species, increased mortality has been observed due to bird and fish predation when entering impoundments.

Throughout the Roadmap, impoundment is used to describe river sections where damming alters the natural flowing environment upstream of a dam structure. An issue associated with impounding a watercourse is where the reservoir levels fluctuate. While the reservoir is full during some periods, at other times, it is drawn down, which can result in dewatering specific habitats, like spawning areas, for instance. Similarly, downstream of the dam, reduction or curtailment of outflow from inundated areas can result in stranding.

The impact is site dependent as it varies from ponded sections altering the watercourse for a few hundred meters to tremendous increases in the inundated area reaching tens of kilometres upstream and covering a wide expanse of land. Where the inundated area is not greater than the naturally flooded areas or beyond, this is classified as a flood plain or terrestrial impoundment.

Figure 3.5 ***Impoundment area for hydroelectric production (Orlik Reservoir, Czech Republic)***
(Source: Kletr/shutterstock.com)

Floodplain Impoundment

The morphological and hydrological changes following such a layout may reduce or eliminate floodplains and associated habitats supporting fish spawning and growth. This may result in an overall reduction in watershed habitat diversity and associated fish diversity by impacting floodplain species. Ultimately, the loss of floodplain habitat can decrease the productivity of entire river systems.

Terrestrial Impoundment

Terrestrial impoundment (commonly termed a reservoir) impairs upstream terrestrial ecosystems through inundation or impoundments, which affects terrestrial vegetation through biomass submergence. Flowing rivers become shallow, standing water or lacustrine littoral and pelagic lake habitats. The extent of the littoral zone will vary if reservoir operations significantly affect water levels. The presence of the reservoir over the longer term may enable vegetation to grow in arid regions, resulting in significant vegetation growth, which may, in turn, increase aquatic and riverine diversity.

When reservoirs are created, there may be considerable periods of low dissolved oxygen (DO) levels or anoxia due to the decomposition of inundated vegetation. This situation may continue until a stable state is reached, which may take decades. In the meantime, it can affect aquatic life in the reservoir and influence passing migratory fish. Upstream fish migration may be significantly affected if fish have difficulty navigating large storage reservoirs with many branches or tributaries. It may also occur to species that maintain the population at lower sections of the river by passive migration (i.e., drifting downstream with the flow) as their smaller specimens may get lost or starve when they end up in reservoirs during their passive migration.

Issues associated with impoundment:

- Transformation of habitat from a lotic to a lentic.
- Destruction of terrestrial habitat.
- Degraded littoral zone and shallow habitats.

Risks associated with impoundment:

- Habitat and biodiversity may be reduced due to the loss of floodplain.
- Low DO levels or even anoxia can occur, possibly lasting for decades.
- Fish migration may be impeded through large reservoirs.
- Increased predation in the impounded section.

3.2.3 SEDIMENT TRANSPORT

Hydropower dams and reservoirs trap sediments that would otherwise pass downstream through normal fluvial processes. The sedimentation process is associated with both the barrier created by the dam and reduced water velocities and shear stresses that characterize hydropower impoundments. These are compounded by the extended water residence times that facilitate settling sediments within the reservoir. This process can effectively capture the river's suspended particulate matter and bed load leading to large depositional areas within the impoundment and, in many cases, a significant eventual loss of reservoir capacity. In extreme situations, transported sediments can enter the power intakes and cause wear and tear to power generation equipment. In other instances, accumulations can reduce turbidity downstream of the dam relative to its natural flow regime due to reduced, suspended particulate loads. However, if inflows or re-suspended lake sediments contain colloidal clay material, they may remain suspended for extended periods.

Sediment transport is variable, generally highest during floods and often negligible during minimum flow periods such as drought and can show a high degree of seasonal and annual variation. In addition, flood conditions can remobilize sediment and transport it downstream.

Sediment and bed load captured by impoundments also affect the downstream environment. Downstream riverine environments can be "sediment starved" such that the reaches below dams may have reduced gravel, sand, and/or sill areas where sediment deposition naturally occurs. This could lead to changes in benthic habitat characteristics, such as reduced areas suitable for the growth of aquatic plants or fish spawning. In other words, if spawning gravel (or substrate) is trapped upstream of the dam and the sediment transport capacity of the river exceeds the sediment supplies downstream, it may lead to bed armouring. The natural consequence of the "starved" state is that the river can "feed" itself with sediment through the riverbed and bank erosion (in middle and lower river reaches too with lower gradients). This may result in riverbed deepening and/or riverbanks becoming unstable and overall yield loss of suitable habitat.

Other issues are related to sediment transport in habitats downstream of larger dams. Flow patterns will generally be more stable, with fewer discharge peaks, and sediment levels will be reduced, except at flushing times. Any changes will affect fish and their habitat, with the nature and severity of impacts being site dependent. Therefore, it is essential that any assessment and monitoring of hydropower operational impacts on fish include any potential zones of the impact that could reach many kilometres downstream of the dam. This includes considerations of any limits or restrictions during periods of migration.

Figure 3.6 ***Illustration of turbid water release from the Three Gorges Dam in China***
(photo credit: Isabel Kendzior/shutterstock.com)

When sediment flushing is part of a sediment management plan for hydropower owners, it will normally occur for two main reasons. It can be considered (or required) as a potential mitigation measure to compensate for "sediment starvation" downstream of the dam. It can also sometimes be used to manage the accumulations of sediments upstream of the dam. In either case, sediment deposits can be flushed through sluices specially designed for this purpose (Figure 3.6). At flushing events, coarser sediment often remains in the reservoir, while finer particles get mobilized. While it is acknowledged that sediments would travel downstream naturally under the free-flowing river regime, flushing would likely produce a more intense loading over a shorter interval of time with a potential increase in turbidity that can pose an unexpected and unnecessary risk to fish (e.g., jamming gills of fish by suspended fine sediments). Therefore, a change in the ratio between finer (suspended) and coarser (bedload) sediments and the consequences shall be considered based on the affected river section (i.e., upper, middle, or lower section; composition of the sediments, source of sediments).

In extreme cases, sedimentation in the reservoir can occur at an elevated rate, causing a rapid decrease in storage volume over a shorter lifespan than preliminarily estimated. This may originate from natural sources such as landslides or changed land-use activities in the catchment.

Issues associated with sediment transport:

- Bedload and suspended sediment deposits in inundated areas will reduce lentic habitat and limit reservoir storage capability.

Risks associated with sediment transport:

- Extreme bedload and suspended sediment deposits in inundated areas may cause significant changes in benthic habitat characteristics.
- Reduced sediment transport to downstream areas may change benthic habitat characteristics.
- Releasing (flushing) large volumes of sediment may increase turbidity, which has severe consequences for downstream water quality and biota and may lead to elevated fish mortality in extreme conditions.

3.2.4 WATER TEMPERATURE AND WATER QUALITY

As noted previously, hydropower development induces changes to a watercourse by obstructing its continuity and impacting natural processes. Disturbance in such processes affects fish communities through water quality changes and their corresponding effect on habitat. Overall, such changes may favour generalist species by reducing the availability of complex habitat characteristics or favouring species tolerant of decreased water quality.

Causes of water quality degradation include:

- Runoff from the catchment, including erosion and anthropogenic sources.
- Decaying organic materials in the reservoir.

Water quality metrics that primarily affect aquatic life include:

- Temperature and stratification in reservoirs.
- Nutrient loads, changes in dissolved oxygen, and production of greenhouse gases.
- Release of supersaturated water downstream.

Changes in riverine physicochemical characteristics and nutrient loads can range from relatively moderate for the smaller RoR plants to significant for developments with large dams. Aquatic habitats can also be affected both upstream and downstream by hydropower impoundments. The effects of changed water quality metrics in the impoundments and the river downstream are discussed individually in the corresponding sub-sections below.

Temperature and Stratification

Example: Altered seasonal temperature patterns from large dams have shown to create downstream problems related to migration timing, spawning, growth and egg hatching for Chinook salmon [3.11].

Unlike lotic habitats (rivers), reservoirs typically have a lower surface area to volume ratio and are not as well mixed; they generally respond slower to short-term and seasonal temperature changes. Thus, this increased thermal mass facilitates heat storage. When combined with limited mixing, it can form temperature gradients within the reservoir and distinct layers of water due to their different densities. This layering effect is known as thermal stratification. The warmer upper layer is referred to as the epilimnion, the cooler lower layer is the hypolimnion, and the distinct temperature gradient or discontinuity between these layers is referred to as the thermocline. Hydropower intakes within reservoirs are often placed under the thermocline. In non-tropical climates, the temperature difference is the opposite during winter, meaning that the upper layer becomes colder (may have ice cover). In contrast, the lower, denser layer is warmer with a 4 °C temperature.

A range of factors determines whether a lake will thermally stratify and how stable this stratification will be. Still, the main factors are climate and latitude, depth, and morphometric characteristics, rate of in-reservoir mixing due to wind, inflow, and outflow rates. The process follows a seasonal pattern in reservoirs or bodies of water predisposed to stratification. In winter, non-tropical reservoirs are generally well mixed. Still, as temperatures increase in spring and summer, surface water warming occurs, increasing the temperature difference between surface and bottom waters, leading to a distinct temperature discontinuity or thermocline. As temperatures decline into autumn, surface waters cool, increasing their density above the warmer water below, leading to “overturning” or mixing the lake.

Stratification can significantly affect water quality and fish in lakes and downstream waterways. In reservoirs or impoundments where stable stratification occurs, mixing between the epilimnion and hypolimnion is virtually non-existent. While dissolved oxygen levels are maintained by phytoplankton and surface mixing in the epilimnion, minimal mixing occurs beneath the thermocline, and lack of light limits primary productivity (Figure 3.7). Decomposition of submerged vegetation and organic detritus further reduces oxygen levels in the hypolimnion, developing anoxic conditions and reducing habitat availability for fish. Anoxic hypolimnetic waters are characterized by hydrogen sulphide production. The extent of these anaerobic processes is influenced by many factors, including the availability of organic compounds from the decomposition of flooded terrestrial vegetation, such that reservoirs generally evolve as biochemical oxygen demand eases in line with the declining availability of flooded organic material.

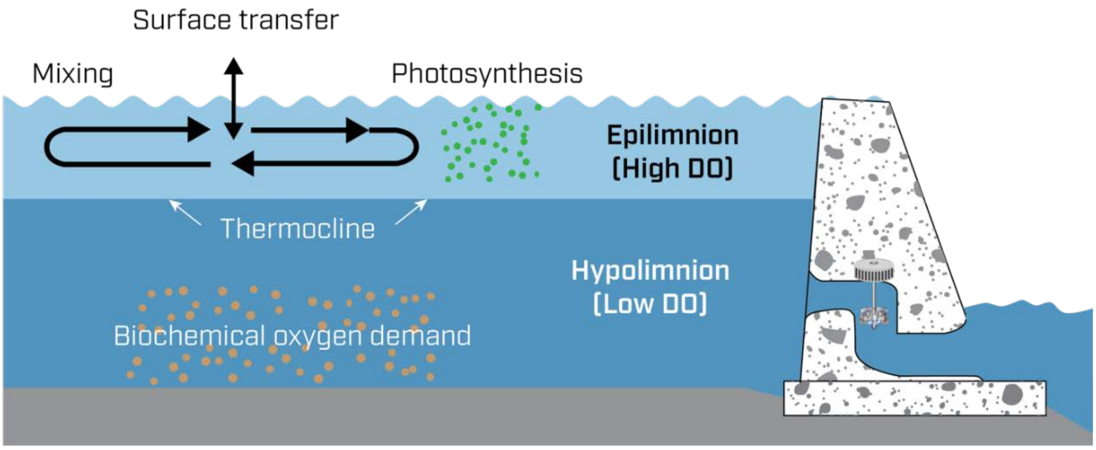

Figure 3.7 ***Illustration of the stratified reservoir*** (Source: SINTEF Energy Research, Norway)

Ultimately, reservoirs will favour different communities of fish than rivers. Heat storage from stratification may act as a barrier to movement or a stressor to migrating fish that mays affect their survival and fitness. On the other hand, connecting reservoirs may also function as refugia for fish migrating upstream if favourable temperature zones and dissolved oxygen exist. Suitable reservoirs may serve as stopover areas in route to upriver spawning.

Temperature changes in reservoirs also affect river sections downstream. Releases of water from the upper layer of the reservoir may be warmer than the temperature in the recipient section. Releases from the lower layers in the reservoir may be oxygen-depleted, affecting downstream water quality and the health and survival of fish and other aquatic organisms. Releases of water from the hypolimnion potentially impact downstream biota.

In general, temperature changes affect fish differently in the reservoirs than those in the river downstream. It includes shifting spawning times and success for cold and warm water species from increased thermal variability. Increased temperatures may cause fish egg or larval mortality or loss of habitat for invertebrate food bases, disrupting food webs.

Issues associated with temperature and stratification:

- As the dam operators draw reservoir levels up and down, resulting thermal gradients will affect fish in the reservoir and downstream of the dam and powerplant.
- Large and deep reservoirs (storage type) respond slower to changes in thermal stratification than shallow ones. Variables include the climate and global latitude.
- A specific situation occurs in cold regions where an ice cover forms on the reservoir in winter.

Risks associated with temperature and stratification:

- As many HPP storage reservoirs are drawn down seasonally, power intakes in the reservoir need low-level or multiple-level intakes. Depending on the intake being operated, the water passing through the power intakes may come with various temperatures at different times and seasons. Sudden temperature changes (due to flows passing through the reservoir or releasing water at the dam from different depths) may affect the health and survival of fish and aquatic organisms.
- Passing flows that exceed power generation requirements can be achieved by operating various combinations of discharge facilities, depending on reservoir levels. This may result in downstream releases having a sub-optimum temperature for downstream fish populations.
- Heat storage in stratified layers may act as a barrier for migratory fish.
- Sudden temperature changes (due to flows passing through the reservoir or releasing water at the dam from different depths) may affect the health and survival of fish and aquatic organisms.
- Altered hatching, energy consumption for aquatic biota, growth, and species-dependent mortality lead to altered age structure and population effects.

Nutrient Loads, Changes in Dissolved Oxygen, and Production of Greenhouse Gases

Chemical changes to water quality can affect both fish survival and growth. These changes may also affect reproductive success and the abundance of food organisms via stressors such as water pollution and toxic algal blooms, particularly in high retention time reservoirs.

Nutrients

Potential water quality impacts from adverse phytoplankton and nutrient profiles may occur in stratified reservoirs. Phytoplankton can affect water quality in warmer conditions, and elevated irradiance levels may favour their abundance near the surface. This can result in higher metabolic activity that can saturate oxygen levels in surface waters, contrasting sharply with lower oxygen or anoxic bottom water layers. Reservoirs may also create conditions that change the surface covering algal communities and support aquatic macrophyte plant growth. Floating macrophyte rafts, such as water hyacinth (*Eichornia crassipes*) in tropical areas, can blanket entire reservoirs in a mat, which shades out phytoplankton and can increase organic matter input and oxygen depletion.

Nutrients, such as phosphorous and nitrogen, often increase from natural biological release and decomposition. However, the same processes that trap sediments in impoundments also capture the organic component of the seston (suspended matter) floating within reservoirs that would usually be conveyed through an undammed river system. This can result in impoundments becoming nutrient sinks which, in extreme circumstances, may become eutrophic (Figure 3.8). Further, large influxes of organic matter, nutrients, or pollution (e.g., fertilizer, sewage, or stormwater) from surface water runoff may also support conditions that lead to eutrophication. This can be problematic as the elevated nutrient levels can promote high phytoplankton biomass, leading to increased turbidity, pH, and decreased light penetration of reservoir surface water and possibly impacting submerged macrophyte biomass. Blue-green algae dominate the phytoplankton community; this can cause toxic algal blooms and associated ecological and human impacts.

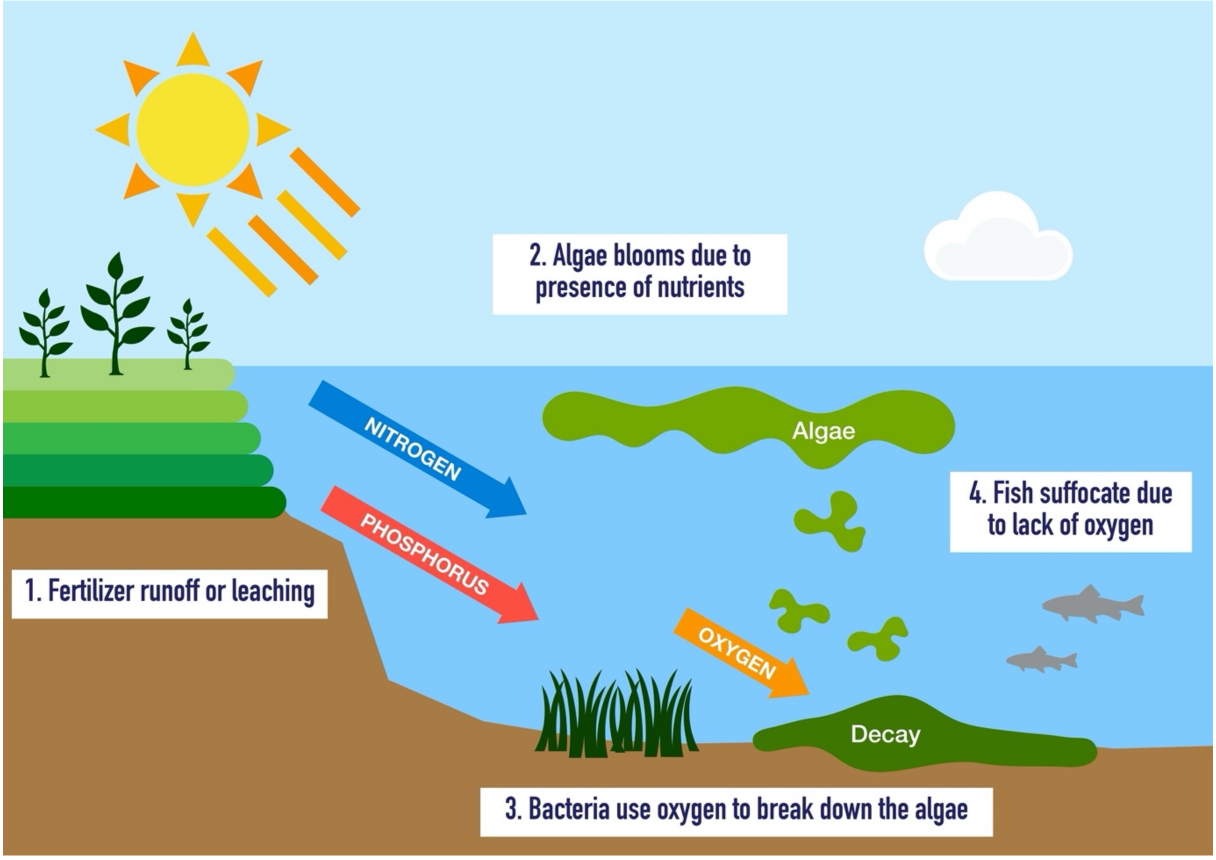

Figure 3.8 ***Illustration of eutrophication or other processes***
(Source: Dimitrios Karamitros/shutterstock.com)

Dissolved Oxygen

DO is an essential factor in water quality. Hydropower dams can significantly affect levels occurring in natural watercourses. Water diverted through a hydropower facility is typically much lower in DO than in the rest of the ecosystem. When this under-aerated water is released downstream, it decreases the oxygen content of the rest of the river, threatening aquatic life below the dam.

Greenhouse Gases

Since the early 1990s, hydropower reservoirs have been identified as a potentially significant source of carbon dioxide (CO_2) and methane (CH_4) for the atmosphere; however, such Greenhouse Gas (GHG) emissions do not affect fish populations directly within the reservoirs; the background biochemical processes and conditions that are risks for fish and the abundance of their habitats. GHG emissions from reservoirs are still subject to large uncertainties. Very few studies document the net GHG emissions from creating a reservoir in a river system. There are often large uncertainties related to the measurements and estimations of net GHG emissions from reservoirs, and there are still heated debates on the topic ([3.12] and IEA Hydro Annex XII).

The real perturbation of the carbon cycle and related emissions due to reservoir creation should consider the cycle and emissions from the whole catchment reservoir's creation and compare this to the situation after the reservoir has been built. Factors unrelated to the reservoir's creation, such as other activities in the catchment that may lead to increased emissions, should not be included in the net concept.

Key parameters that determine the GHG emissions are related to the age of the reservoir and other water quality metrics such as concentrations of dissolved oxygen, water temperature, water residence time, organic matter concentrations, supply of nutrients, and biomass of plants, algae, bacteria, and animals in the reservoir.

Gas exchange between aquatic ecosystems and the atmosphere occurs mainly through two different pathways:

- CO_2 and CH_4 can be transferred by diffusion from or to the aquatic ecosystems through the air-water interface. This pathway is called diffusive flux and is based on the difference in partial gas pressure between the air and the water.
- Bubbling fluxes correspond to the direct transfer of methane from the sediment to the atmosphere. In sediments receiving a large amount of organic matter by sedimentation, methanogens are very active and CH_4 accumulates in the sediments. Bubbles develop if the CH_4 concentration in the sediment pore water exceeds its maximum solubility in water. Bubbling fluxes mainly occur in the shallow parts of lakes, rivers, and reservoirs (<10 m).

In addition to these pathways, GHG can be emitted downstream of the dam (*downstream GHG emissions*). This additional pathway includes diffusive emissions from the river below the dam and the degassing at the power station. Degassing occurs when water containing dissolved methane is drawn through the turbines or spillway gates. Then most of the gas is released downstream due to pressure change. Figure 3.9 illustrates processes and pathways related to GHG emissions from reservoirs.

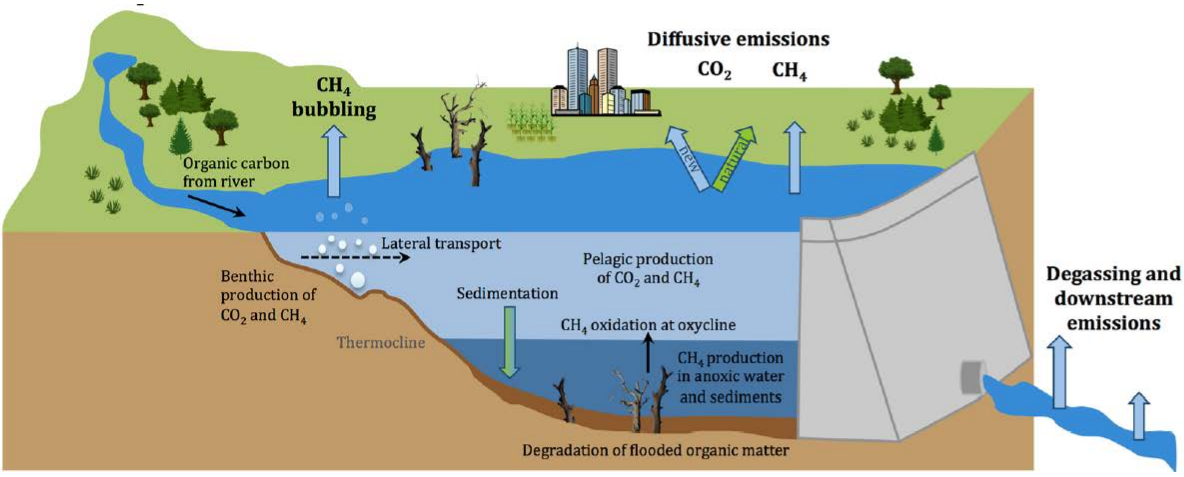

Figure 3.9 ***Processes and emission pathways in reservoirs***
(Source: [3.13])

Issues associated with nutrient loads, changes in dissolved oxygen, and production of greenhouse gases:

- Reservoirs become nutrient sinks and turn eutrophic, causing toxic algal blooms in extreme cases.
- Water diverted through storage HPP normally has low DO levels, which decreases oxygen levels downstream of the dam.

Risks associated with nutrient loads, changes in dissolved oxygen, and production of greenhouse gases:

- In general, chemical changes to water quality may affect fish survival and growth.
- Anaerobic processes in hypolimnion may reduce available habitats in the reservoir.
- Changes in water quality may affect fish reproductive success and the abundance of food organisms due to stressors such as water pollution and toxic algal blooms, particularly in high retention time reservoirs.
- When GHGs or under-aerated water are released downstream, it may decrease the oxygen content of the rest of the river and threaten aquatic life.

Supersaturation

In addition to the risk of releasing water with low DO levels, some impoundments may also be predisposed to releasing water with high dissolved gas levels. The solubility of gases correlates positively with pressure. When Total Dissolved Gas (TDG) levels in the water exceed 100% on a given ambient pressure, it becomes oversaturated. The state is referred to as supersaturation. Such a situation can negatively affect aquatic life. When fish and invertebrates are exposed to gas supersaturation, they risk the formation of gas bubbles in tissues and blood vessels. This condition can alter the behaviour of an individual fish. It might cause other sub-lethal or chronic effects (i.e., increased stress level, increased susceptibility) and increased mortality depending on the tolerance level of the species in different life stages. Some fish species may navigate themselves into deeper areas to compensate for oversaturation; however, if adequate depths are not available, the risk of gas bubble disease increases.

There are scenarios where supersaturation may occur, such as high energy spillway discharge into deep plunge pools, air entrainment into power intakes of medium to high-head power stations, and air injection systems into the turbine to reduce cavitation [3.14]. Supersaturation may happen naturally (i.e., primarily downstream of waterfalls due to plunging). However, with the modern era of river regulations for hydroelectric purposes, more severe instances are reported periodically. Awareness of such cases increases as they pose challenges to the fish communities downstream of the powerplant.

Discharges past a dam (through spillways, weirs, sluices, or other discharge facilities) can cause supersaturation downstream of the barrier [3.15]. While the whitish colour of the water surface can be easily recognized (Figure 3.10), it usually causes minimal risk to downstream fish populations for low-head structures unless it blocks the entrance of the upstream fishway facilities. However, the risk proportionally increases with the height of the dam.

Air admission may occur or be injected into the power flows, primarily at the turbine units, to enhance operational conditions at the hydropower plant (e.g., reducing cavitation). Such hydropower practices can lead to oversaturated water releases, threatening the fish communities downstream of the power outlet.

Figure 3.10 ***Near-surface supersaturated "white-water" release from small-scale HPP in Canada***
(Source: Pi-Lens/shutterstock.com)

High levels of supersaturation can occur at high-head hydropower plants. Air can be entrained into the water flow during operations in tunnels, steep shafts, and penstocks. It dissolves under elevated pressure in the system before reaching the turbines. Challenging situations have been observed in systems with uncontrolled creek intakes. Passing the turbine, the pressure drops to atmospheric, but water may not reach gas equilibrium rapidly. Therefore, with high levels of dissolved gases, it becomes supersaturated. Even though outgassing reaches an equilibrium state (when TDG is 100%) under highly turbulent conditions with sufficient river depth, the degassing process might be slow and supersaturated water can be transported several kilometres downstream. Aquatic life is exposed to extreme threats in the affected reaches until gas equilibrium is reached.

Issues associated with supersaturation:

- When the TDG level in water exceeds 100%, supersaturation negatively affects aquatic life, causing Gas Bubble Disease in fish and aquatic organisms, resulting in episodic fish mortality and decreased prey abundance in downstream rivers.

Risks associated with supersaturation:

- Spillway discharges falling from high-head dams may create high pressure in the plunge pools, causing gases to be dissolved at a high rate.
- Supersaturated water may be carried a long way downstream of the barrier. It may hamper fish movement if the de-aeration process is slow, or TDG is high.
- Severe supersaturation may occur at high-head hydropower plants equipped with Francis turbines, with entrained and dissolved air reaching the turbine chamber. Here it dissolves under the elevated pressure, passing the turbines, the pressure drops, and the water becomes supersaturated, affecting fish populations downstream.
- Air injection or admission at turbines can oversaturate the water released downstream.

3.2.5 REGULATED FLOW AND WATER ABSTRACTION

The primary ways river flow regimes are impacted by hydropower are through spatial and temporal alterations, including altered flow patterns resulting from operations, the total loss of flow, changes to river connectivity, and water volume gains or losses associated with inter-basin transfers [3.16].

SPATIAL ALTERATIONS: FLOW DIVERSION

Hydropower flow diversions vary by facility type (RoR, storage HPP, and PSP), depending on the catchment, project site, facility design, operation following conditions set by the license, and water allocation.

Hydropower development and operations can disrupt flow regimes in riverine ecosystems in several ways that result in numerous physical and biological changes. Flow diversions associated with hydropower operation may lead to uneven flow distributions within and between watersheds, disrupting the movement of aquatic species, sediment, organic matter, and nutrient flows. Water diversions at hydropower facilities and river channelization and inter-basin transfers have environmental impacts on a global scale [3.17].

Further impacts of flow diversions are discussed below and linked with three system configurations: storage HPP with bypass reaches RoR, and inter-basin transfers.

Storage HPP with Bypass Reaches

There are generally two main types of HPP with reservoir storage: those with a powerhouse at the dam and those that divert power flows at the dam through a bypassed reach (i.e., tunnels, flumes, conduits, penstocks, among others) to a powerplant. Subsequently, flows are returned to the original river channel. This latter case is considered in this section (Figure 3.11).

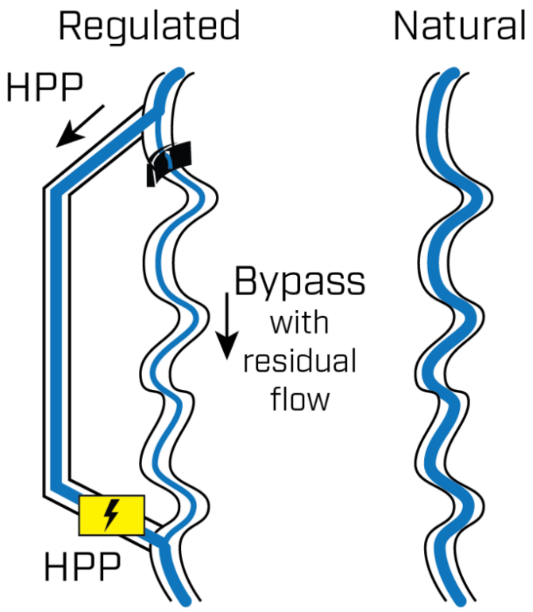

Figure 3.11 ***Illustration of bypass reach with limited water flow***
(Source: SINTEF Energy Research, Norway)

Bypass reaches are the sections of the regulated waterway between the power intake and the tailrace channel that receive flows from spillway discharges or residual flow releases for fish (either minimum, instream or environmental flow) [3.18]. To provide conditions favourable for efficient power production, bypass reaches are commonly located along rivers with a steep gradient. Flow requirements in bypass reaches are typically set as part of project permitting and licensing conditions. Reservoirs with sufficient water inflow for storage have more potential to control flows in bypass reaches to meet environmental management objectives and avoid releases that might negatively impact ecosystems.

A total loss of flow will eventually result in a dewatered bypass reach. A significant baseflow reduction that causes perennial channels to dry out can lead to potentially irreversible species loss and degradation of ecosystem services [3.16]. In addition, changes in connectivity due to flow diversions may limit the exchange of organisms and inorganic and organic materials between upstream and downstream reaches, including the bypass reach. Similarly, flow diversions and reductions in flooding can restrict the lateral connectivity downstream of the dam between main river channels, secondary channels, and peripheral floodplains.

Hydropower dam operations may affect bypass reach conditions in other ways beyond flow partitioning. For example, in regions where winter ice formation is typical in bypass reaches, changes in power plant operations, such as unit starts and stops, may lead to ice breakup (this may also occur in the reservoir), rapid dewatering, and subsequent environmental impacts downstream [3.19]. In other regions, long bypass reaches may lead to environmental issues.

Example: Some HPP projects have been designed in tropical systems low-head with long bypass reaches. For example, the Belo Monte dam in the Xingu River, Brazil, has a bypassed reach of 100 km in the river bend, namely Volta Grande do Xingu. Such systems pose significant challenges for developing mitigation solutions and often create issues in maintaining fish populations due to alteration in flow discharge and habitat availability

Run-of-River

As in the case of storage HPP with bypass reaches, a similar distinction can be made between those projects with a powerplant at the headworks and those where power flows are diverted to a powerhouse remote from the headworks. In this latter case, the issues associated with bypass reach for HPP projects are like those for run-of-river schemes. The main difference is that while storage HPP projects have a reservoir and can control the residual flow released to the bypass reach, RoR schemes have no storage capacity and generally discharge inflows. Unless there is no obligation to the hydropower owners regarding flow control in the bypass reach, these flows are generally through the power generation units. In these cases, the flow rate exceeds the turbines' rated discharge capacity (except for riparian flows), with any excess flows to the bypass reach. Thus, flows in the bypass reaches of run-of-river schemes are usually more variable than those for storage HPP projects. These flows are usually unexpected in timing, frequency, magnitude, and duration. Fluctuations may reduce fish habitat quantity and quality, cause fish displacement, and negatively affect fish survival, fitness, and growth [3.21].

HPP with Inter-Basin Transfers

The primary issue related to inter-basin transfers is that they impact two or more river systems: the recipient basin receiving supplemental flows from the donor basin [3.16]. Such transfers are typically done to alleviate water scarcity or enhance hydropower generation. Diverting water from one watershed to another may introduce new species that compete with native species, potentially declining. Inter-basin transfers may also be detrimental to fish that utilize distinct signatures from rivers and basins to inform movements and complete their life cycles, such as salmon that use olfactory cues for natal homing to specific rivers and streams for spawning. Little is known about the effect of inter-basin transfers on fish natal homing. Researchers found that trapped and transported juvenile salmon have reduced homing success [3.22]. At the same time, another study showed that fine-scale habitat changes affected the precision of fish homing [3.23]. Another concern is the introduction of hatchery-raised salmonids from inter-basin transfers into rivers with native breeding populations [3.24]. It is worth noting that with the continuously increasing effort and research to minimize the negative impact of any hydropower project, new HPPs with inter-basin transfer would be most unlikely to get approved due to the large uncertainties and effects on two different river basins at the same time. A general exception is when the hydropower has an outlet to the sea, a powerplant with inter-basin transfer has been built to power local industries with intensive energy demand.

Issues associated with spatial alterations:

- Perennial channels dry out or completely disappear in bypass reaches due to insufficient flow regulation causing significant environmental damage.
- Disruption of flow regimes results in numerous physical and biological changes to the system.

Risks associated with spatial alterations:

- Flow diversions may lead to uneven flow distributions within and between watersheds.
- Flow diversions can disrupt the movement of aquatic species and sediment transport, organic matter, and nutrients.
- Introduction of new species from inter-basin transfers.
- Uncertain impact on fish natal homing.

TEMPORAL ALTERATIONS: OPERATIONAL STRATEGIES

The most significant temporal alterations to flow regimes are related to operational strategies. These are based on the type of facility (RoR, storage HPP or PSP) and meet both electricity system requirements and environmental and safety protocols. Due to regulation, there are also seasonality changes that may affect fish's fitness. Strategies that affect fish can be categorized as conventional and flexible operations, sometimes combined with environmental measures.

Conventional Operation

Various temporal changes are associated with flow distribution related to the formation of a barrier. When natural patterns are smoothed or disrupted by regulation, fish community productivity and biodiversity are often reduced. Regulated flows can disrupt spawning patterns and recruitment success, ultimately leading to the alteration of community structure. Regular flow releases from a barrage or dam may leave much fish stranded downstream and susceptible to predation. Furthermore, fish mortality may increase if sediments are released in excessively high amounts, as part of flushing activities for reservoir management; this can subsequently impact downstream water quality and aquatic habitats.

Reservoir level fluctuations influence upstream hydro-morphology and habitat quality. A rapid drawdown can affect juvenile and reproductive-age fish by reducing the availability of suitable habitats and impacting the macroinvertebrate prey base of food webs. In extreme cases, water drawdowns may cause significant aquatic vegetation in affected areas to desiccate and perish. Flat shore zones are the most critical habitats affected by alteration in reservoir water levels, particularly if the frequency of water level variability results in large areas frequently dewatered, making them unsuitable as productive aquatic habitats.

Issues associated with the conventional operation:

- Reservoir drawdowns expose large areas for long periods causing significant areas of aquatic vegetation to desiccate and perish.

Risks associated with the conventional operation:

- Flow variability may disrupt spawning patterns and limit recruitment both in the reservoir and downstream.
- Regulated flows may lead to alteration of community structure.
- Regular releases from a barrage or dam leave fish stunned and susceptible to predation.
- Significant sediment releases in critical periods may increase fish mortality downstream.
- Desiccated vegetation, because of deep drawdowns, or large areas of flat shoreline zones, may affect the habitat in the reservoir.

Flexible Operation (Hydropeaking)

Flexible operation of HPP may lead to severe flow pulses into tailrace waterbodies. This phenomenon, also known as ramping up and down (Figure 3.12), or hydropeaking, is associated with storage HPPs and PSPs operation. It is commonly driven by price optimization and the need to balance fluctuations or provide peak load energy into the electricity grid due to the increasing number of VRE sources [3.25].

Hydropeaking can significantly impact fish if plant operations are not managed appropriately. Flow variability due to hydropeaking often results in frequent dewatering of aquatic habitats, a large magnitude of flow variability over short periods. The increased hydraulic shear stresses across riverbeds can harm aquatic ecosystems [3.26]. The most vulnerable organisms to hydropeaking are juvenile fish through increased mortality from stranding, trapping from pools, or increased predation [3.27][3.28]. Further impacts of hydropeaking may include increased macroinvertebrate drift and decreased species diversity. In addition, significant ramping of tailwater discharges can affect fish and their ability to follow the "attraction" pathway for upstream fish passage. These impacts are mainly influenced by dewatering rates, river bathymetry, and distance from HP outlets [3.29].

In some cases, flow releases from the flexible operation may also be associated with changing water quality. It is termed thermopeaking when power flows have significantly different water temperatures than in the recipient watercourse. It is termed saturopeaking when supersaturated water is released during hydropeaking.

The ecological impact on fish from HPP with tailrace outside rivers is largely insignificant.

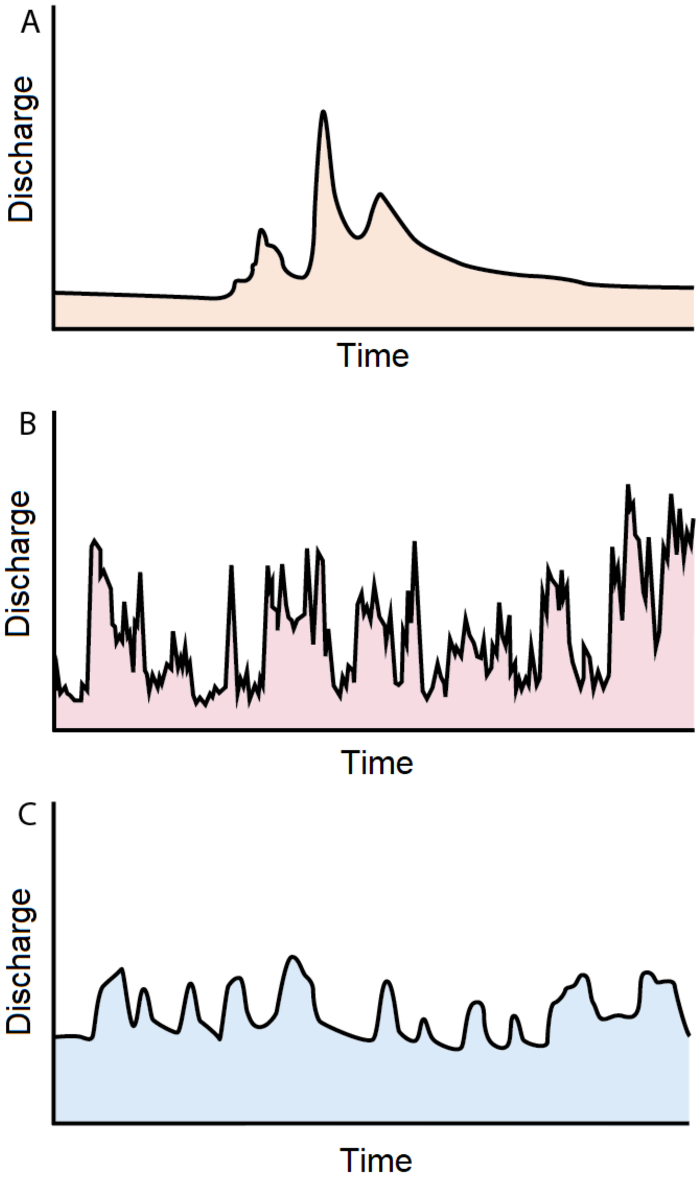

Figure 3.12 ***Conceptual characterization of three fluctuating flow types, such as time-series of flow from heavy rainfall (A), strong hydropeaking (B), and moderate hydropeaking (C)*** (modified from: [3.30])

Issues associated with the flexible operation (hydropeaking):

- Increased hydraulic shear stresses across riverbeds significantly alter habitats.

Risks associated with the flexible operation (hydropeaking):

- Fish may become stranded.
- Spawning areas may become dewatered.
- Increased drift of eggs, larvae, fry, and juvenile fish.
- Changes in fish assemblages.
- Frequent flow variation can result in reduced aquatic habitat and population decline.
- Hydropeaking flow may disrupt attraction flow towards upstream fish passage facilities.
- High tailwater discharges may be encountered due to unusual operational situations.

Environmental/Multipurpose Operation

There is also an aspect that needs to be considered in hydropower systems where flow regulation protocol for ecological purposes or other water management services (i.e., irrigation, water supply, and recreational services, among others) has already been applied. Setting conditions for aquatic communities is challenging, particularly in diverse and complex species assemblages, and may require identifying additional trade-offs to be evaluated in the context of fish population and restoration goals. Ideally, the evaluation process follows environmental policies and guidance and is performed before the construction of hydropower facilities (see Section 2.6). Of note, when there is a possibility to design flows for supporting fish, it may unintentionally create conditions that promote artificial species selection. It has an elevated risk at watercourses with a cryptic population structure (i.e., more than one genetically distinct population managed as one unit).

Issues associated with environmental/multipurpose operation:

- -

Risks associated with environmental/multipurpose operation:

- Insufficient flow regulations for ecological purposes may promote the artificial selection of species, changing the community composition and structure.

3.3 Construction of New and Major Refurbishment of Existing Hydropower Plants

Construction of New Hydropower Plants

In most jurisdictions, developing new hydropower projects will include comprehensive habitat and connectivity requirements as part of their environmental and social approvals stage. This would also cover the construction phase, mainly when structures are built in or adjacent to the original river channel (Figure 3.13). At this time, the natural river flows need to be diverted, and flow conditions become altered. Flow diversions are usually created by cofferdams and can include tunnels through the abutments or past or partly completed structures. Maintaining fish connectivity can be extremely challenging during this phase, as effective mitigation measures may not have been incorporated into the construction plan. Therefore, there is a risk that increased flow velocities in the constricted river channel may impede fish passage in both upstream and downstream directions during the diversion. Besides connectivity, construction waste contaminates water quality, affecting fish populations and downstream habitats.

Figure 3.13 ***Construction site of a hydropower project in Nepal***
(Source: orin/shutterstock.com)

During the later phases of construction, when most of the civil works of the dam are completed and before the units are commissioned, there is normally a period when the natural river flows are passed either over or through the dam. Flows passing over the spillway can pose problems to the fish communities downstream, especially for high dams. When water plunges into deep pools, this can lead to significantly high TDG levels, which may last for several kilometres in the downstream reaches of the river. This can threaten fish species and aquatic life, as discussed in Section 3.2.4 [3.14].

Redevelopment of Ageing or Redundant Hydropower Plants

The redevelopment of ageing or redundant hydropower plants is, by definition, the complete rebuild of the existing but redundant powerplant and may or may not include changes to the other infrastructures, such as dams and discharge facilities. Redevelopment usually entails upgrading the output of the hydropower plants and/or providing increased energy and water management services. Redevelopment can have many similar impacts on fish as new construction. Still, the main difference is that any construction can use the existing infrastructure in many ways, depending on both the old plant’s layout and the new one’s design, which can affect the impact on fish. Before finalizing the redevelopment process, the impact on fish can be estimated depending on the different practices under consideration.

Refurbishment of Ageing Hydropower Plants

Hydropower plants generally need to undergo a modernization process after 30 to 40 years of operation; this can range from updating critical machinery and electronic controls to a complete refurbishment or redevelopment of the site. Also, many operational licenses must be renewed after 30 to

50 years of operation. Many existing hydropower plants, especially older ones, may not have included consideration of fish passage in their original design nor any environmental mitigation measures in the original licensing process. Any requirements were usually limited to upstream passage facilities and incorporated fish passes. It is also possible that some form of upstream fish passage facilities might have been added as a retrofit [3.31].

For ageing hydropower plants, it is unlikely that any form of a downstream fish passage or other relevant mitigation measures were considered in the original design. However, nature conservation initiatives are increasing worldwide. As for new hydropower plant developments, jurisdictions for renewing licenses of existing HPPs will include strict environmental requirements during any refurbishment works. During this phase, the main ecological challenges are those discussed for building new hydropower plants, meaning that flows may change, construction may impede fish passage, and waste may contaminate water quality. However, because most refurbishment only covers part of the original hydropower plant development and there is usually a desire to keep the plant operational, designing and maintaining fish connectivity and providing any other necessary mitigation can be complex.

Issues associated with refurbishment or redevelopment of ageing hydropower plants:

- No consideration was given to fish passage in the original design and construction.

Risks associated with refurbishment or redevelopment of ageing hydropower plants:

- Adequate fish connectivity may not have been provided or maintained from the original construction.
- Construction waste may contaminate water quality (increase turbidity), while turbines are not operating but the dam is built.
- Supersaturation may be a problem during construction when flows spill over high dams into deep plunge pools.

SECTION 4. HYDROPOWER AND FISH: SUSTAINABLE OPTIONS

Section 4 highlights sustainable options that address the competing interests described in Section 3. The section starts with a brief historical overview of nature conservation efforts that evolved along with hydropower development. This is followed by the options associated with the five primary processes encountered: i.)39 fragmentation, ii.) impoundment, iii.) sediment transport, iv.) water temperature and quality, and v.) regulated flow and water abstraction. It should be noted that while the Roadmap introduces measures addressing all processes, it presents more extensive coverage of the variety of fish passage solutions, as fragmentation is the foremost challenge associated with hydropower projects in the minds of the public.

The **various challenges** are emphasized with **bold text in red** throughout Section 4. They are commonly referred to at the beginning of each sub-section. The **different options** to address them are presented as **underlined and bolded green text** with short descriptions. At the end of this section, the challenges are combined with the options in Tables 4.6 – 4.10 to provide the reader with a quick overview.

4.1 Conventional and Emerging Measures

As the hydropower industry's development evolved, so did public awareness of its impact on freshwater ecosystems. Among the main challenges, perhaps fragmentation has been targeted from the earliest times. Fish passes (also called fish ladders) were installed at some of the original hydropower plants, dating back to the 19th century in Europe and North America. Hydropower stations developed significantly globally from the early 20th century with different characteristics. Indeed, in many cases, the effort was made to allow fish passage over the dam, although with questionable efficiency at the beginning. Other negative impacts on the environment, especially on fish habitats, have been slowly identified over decades of operational experience.

In early times most of these impacts were overlooked. However, with increased environmental awareness, research programs started investigating the causes and their impacts. Some watercourses have shown evidence of dramatically reduced or eliminated fish populations due to developed anoxic conditions, the release of toxic elements, loss of food source habitat, and other causes (as noted in Section 3).

Like developing a new hydropower system, selecting the most appropriate mitigation measures will depend on jurisdictional regulations and legislative requirements. **However, in regions where such legislative requirements are weak, non-existent, or outdated, it is highly recommended that hydropower investors voluntarily follow accepted international standards. Failure to do so can jeopardize the overall long-term social acceptance of the project, as a result of not addressing ecological needs appropriately. In such cases, projects may be forced to retrofit mitigation measures, which is usually more costly than implementing them during the design phase.** In addition, location-specific factors also limit the type of effective mitigation. These include hydropower system design and operational requirements, site characteristics, fish species assemblage, ecological requirements, social expectations, and overall budget considerations.

Moreover, it is more challenging to synchronize the natural conservation efforts in several hydropower plants in the same watershed. Still, it points towards integrated watershed management, representing state-of-the-art methodologies. In conclusion, hydropower development requires a holistic approach that addresses all the challenges identified in each watershed to reduce any negative impact on nature and assure sustainable utilization of the technology.

In many cases, hydropower development is not the only factor responsible for all the challenges emanating from dams and river regulation in the watershed. Dams and other civil works are often built for water management services and hydropower. These include flood and drought management, fluvial navigation, and water allocation for irrigation, industrial, recreational, and environmental use. Therefore, it is unrealistic to expect hydropower development to address all the challenges in these conditions. Effective mitigation requires a joint effort from all the involved stakeholders.

4.2 Fragmentation

The construction of dams and weirs is a major threat to riverine fish populations and is particularly harmful to diadromous fish. Parallel to industrial development and the associated increase in anthropogenic impacts, many **fish passage facilities (also known as fishways or fish passes) of various technical, natural, and alternative designs and options** have been constructed and tested to mitigate fragmentation for upstream migratory fish on the first place (Figure 4.1). There is a long list of fishway successes where a suitable design matches the ecological needs' physical requirements, including the target species. At the same time, numerous examples demonstrate that successful fishway migration can be challenging [4.1]. Problems are usually associated with non-suitable design and/or operation for targeted species, lack of maintenance, or non-attractive or hardly discoverable fishway and/or bypass entrances.

Past research suggests that fish migration problems must be solved through knowledge of biological aspects, such as fish behaviour, capabilities, and migratory strategies considering both upstream and downstream fish migration. Also considered are engineering design, analysis such as local hydrology, development of suitable hydraulic conditions in fish passes, and civil works that are compatible with the facility's operational requirements. Finally, reliability over time requires that facilities are regularly monitored, inspected, and maintained.

Figure 4.1 ***Fish passage facility at the right riverbank of the Winchester Dam, Oregon, in the U.S.*** (Source: EWY Media/shutterstock.com)

*Note from the authors: Given the importance of site-specific variables, it is outside this Roadmap's scope to provide a detailed discussion on all possible passage mitigation options and specific recommendations on their application. For this reason, only a summary is provided here, intended to provide general guidance on standard applications. It is highly recommended that the final selection process is guided by advice from a fish passage specialist supported by site-specific information. Further background information and performance reports can be obtained from the references listed throughout Section 4.2 and in the **Appendix** (available separately).*

4.2.1 DESIGN BASIS AND CRITERIA FOR FISHWAYS

The design basis and criteria to be considered in selecting the appropriate fishway depend on the fish to be passed and the type of hydropower facility. The design features of fish pass facilities depend mainly on the following factors (independent of new or existing hydropower):

- The target fish species and their key biological characteristics, including their size and life stage, swimming ability, and migratory behaviour.
- River hydrology, affected by hydropower regulation in terms of magnitude, duration, and rate of change of flow.
- The general design and location, as determined by topographic surroundings, the layout of the hydropower structures, operating characteristics, and water levels.
- Key hydraulic design factors include water level gradient (slope), depth, velocity, turbulence, and energy dissipation across the full operating range.

Fish species have a wide range of migration patterns: their physical ability to jump, swim, and climb over different heights, their swimming endurance, and their preference for resting zones on their upstream journey. These variables will define the hydraulic framework for efficiency measures. They should be determined for the fish community that requires passage.

Consequently, planning an efficient fish pass starts with a thorough biological study of the existing fish community upstream of the hydropower structure. Next, the actual hydropower site will set physical limitations to what kind of fish passes are possible to construct, particularly the total height of the dam and the available space on the adjacent riverbanks. These variables can also be used to design single or multiple fish passages, covering the entire range of fish species of ecological or social values for their two-way migration while preventing or restricting the upstream passage of pest-invasive species.

4.2.2 FISH PASSAGE OPTIMIZATION

A paradigm shift needed for fish passage past hydropower plants is the importance of considering adaptive designs. As the hydropower frontier moves towards mega-diverse rivers, designing effective fishways for all migratory species becomes more challenging. The fish passage has been primarily designed to provide continuity of migratory routes for diadromous species that are obligatory migrants. Mega-diverse rivers present a gamut of potamodromous species with various life histories, including long- and short-distance migrants (resident fish and aquatic invertebrates included), with varied swimming and body size traits, moving up and downstream at different times of the year, posing extra challenges to define a set of ecological needs. In such cases, the adaptiveness of a fishway(s) is crucial to ensure that efficiency can be enhanced in case the initial set target is not achieved.

Despite the high level of experience in designing and operating fish passages, particularly for upstream migratory fish, recent studies have shown that many are ineffective, and many fish have difficulties migrating [4.1][4.2]. To address such challenges, the design of an individual fish passage can be optimized. Ways include reducing negative stimuli and trauma for fish during passage (like turbulence and shear stresses) or carefully positioning the facility. For optimization of existing or new designs of a fish passage facility, the following project steps are recommended:

(I) Identify and utilize existing fish migration corridors through fish monitoring.

(II) Consider the behaviour and biomechanical properties of target fish species.

(III) Map and match the hydraulic conditions of the site with the possible passage technologies. Use field flow measurements or simulation and a variant study to (I) and (II).

(IV) Evaluate the mitigation potential of passage technologies.

(V) Integrate operating conditions and hydrology of the respective site. Different flow regimes must be considered to achieve adaptable performance in real time.

More elaborated information can be found in [4.3][4.4][4.5][4.6].

Note that many steps for optimization also relate to the factors required for fishway designs. To this end, several solutions, methods, tools, and devices have been tested and documented, such as:

- Upstream and downstream fish passage technologies.
- Various Computational Fluid Dynamics (CFD) software and/or field equipment, such as the Acoustic Doppler Current Profiler (ADCP), to characterize flow conditions on-site and through simulations.
- Various hydroacoustic and telemetry devices for fish and fishway performance monitoring.

For detailed information, see FIThydro Deliverables 2.1 and 2.2 and [4.6].

Further suggestions for upstream and downstream passage optimization are found in Section 4.2.4 and Section 4.2.6, respectively.

4.2.3 UPSTREAM FISHWAY FACILITIES

Although conventional fishway facilities allow two-way fish passage through or past the barrier, they are more critical to species swimming upstream. Also, downstream fish passage facilities often have different requirements for successful implementation (See Section 4.2.5). Since passage alternatives are usually more limited for upstream than downstream migratory fish, designing, positioning, and operating suitable facilities for the considered fish populations is essential.

Upstream fish passage facilitation measures can be divided into two principal groups:

Volitional measures use fish passage structures that complement fishes' migration behaviour and swimming capability to facilitate passage. They include technical fishways such as pool and weir, vertical slot and Denil types, nature-like fishways, emerging technology fishways, and climbing species fishways. Within the Roadmap, we term volitional measures as fish passage facilities in which individuals must navigate the entire passage.

Non-volitional measures use mechanized methods to transport fish past structures. They also assist fish passage through the exploitation of the migratory behaviour of fish. The principal non-volitional measures are lifting and pumping facilities or trap and transport. In the Roadmap, we term non-volitional measures as those where fish voluntarily encounter the entrance and collection system and where further assistance is provided to the individuals to allow passage over the barrier. **Selected examples of volitional and non-volitional approaches are briefly discussed in the following paragraphs, except for those classified as emerging technologies and usually alternate versions of well-proven measures. Therefore, it should be noted that while the list of types is incomplete, it provides the reader with practical information regarding the different approaches.**

Technical Fishways

Pool-type fishways for upstream fish migration are generally made in concrete, stone, wood, metal, or blasted in rock. They are known as technical fishways due to their detailed design elements and consistent hydraulics. At the same time, they require a small area for implementation compared to nature-like fishways. The most common technical fishway designs include Vertical Slot, Pool and Weir and Denil, with various variations and innovations around these principal designs.

Vertical slot fishways consist of intervening pools separated by vertical baffles that reduce hydraulic energy and provide velocity refuges for migrating fish (Figure 4.2). Water flows through single or multiple vertical slots in each baffle. In addition to channel slope and pool size, the slots' number, shape, and dimensions are key in determining their hydraulic performance and, consequently, their suitability for target fish species.

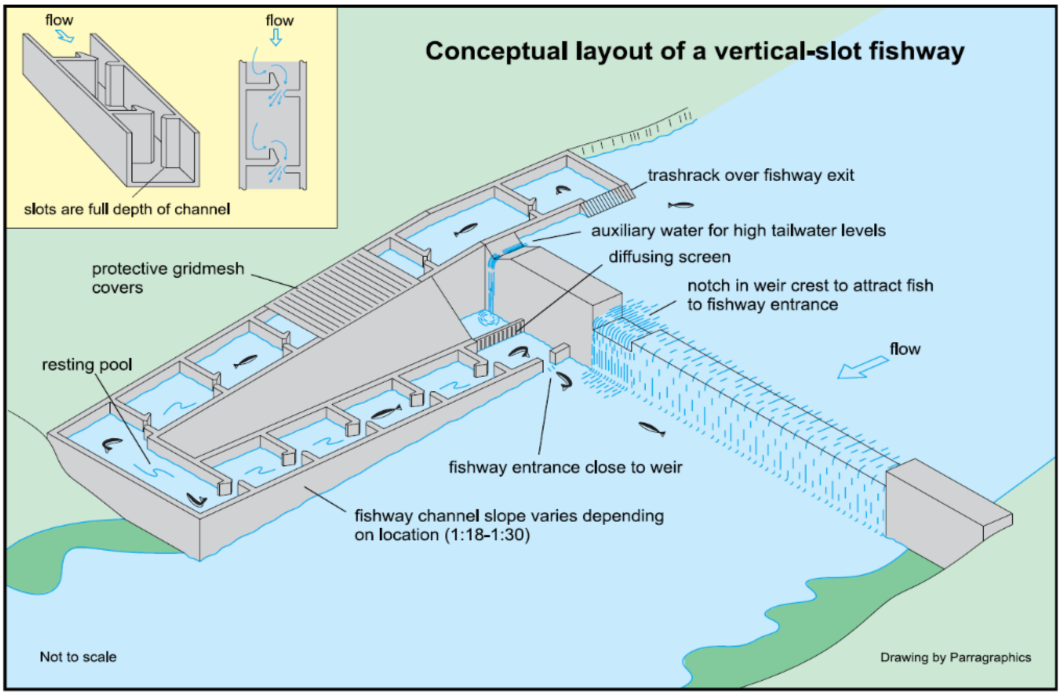

Figure 4.2 ***Concept of a vertical slot fishway layout*** (Source: [4.7])

As the name suggests, **Pool and Weir fishways** consist of interconnected pools and low weirs situated along a gradient. Weirs can be a simple straight profile or use U or V-shaped profiles, and some designs also have a submerged orifice. They are widely used in different applications.

One common variant is the **Trapezoidal fishway** as an emerging technology. It uses design elements from *pool* and *weir* and *vertical slot* fishways to provide hydraulic diversity suitable for small and large fish species, using baffles in a concrete channel.

Denil fishways use a series of vertical U-shaped baffles fabricated from various materials, including concrete, metal, and fibreglass. They are typically mounted in a concrete channel (Figure 4.3). Their prefabricated design makes them suitable for new installation and retrofitting existing fishways. They are widely used and well-known and can operate at relatively steep slopes. Commonly, they are recommended for strong swimmer migratory fish, e.g., adult salmonids and trout. Due to their high flow velocity, they may be quite selective and not functional for juvenile and weak swimmer species.

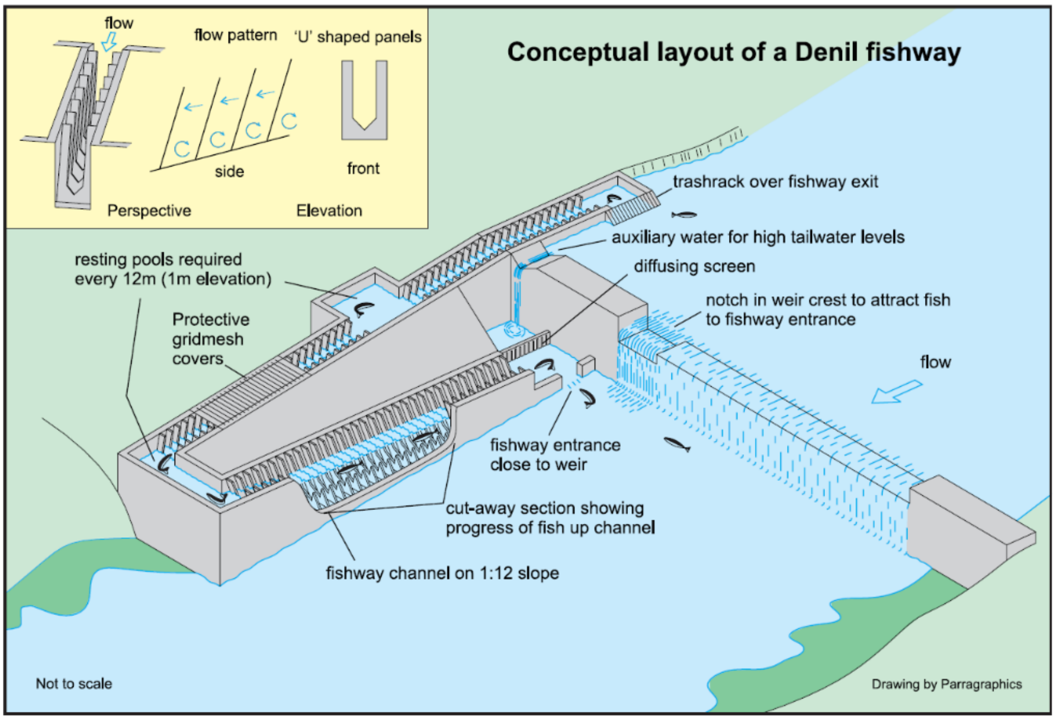

Figure 4.3 ***Concept of a Denil-type fishway*** (Source: [4.7])

Nature-like Fishways

With more focus on biodiversity, nature-like fishways have been developed to mimic natural river channels. The concept is to create a migration corridor navigable for all fish species; recent studies indicate that even aquatic creatures with poor swimming capabilities, like crayfish, snails, and aquatic invertebrates utilize such channels. In addition, they may also provide tiny habitats to smaller species. Nature-like fishways can generally be split into two main categories, bypass channels and rock ramp fishways.

Nature-like bypass channels generally divert a small proportion of the river flow through a simulated natural channel adjacent to the river (Figure 4.4). They are described as nature-like because channels can be constructed to resemble the characteristics of a natural stream. Moreover, they can sometimes be designed to host living places for smaller species. This can be especially important when key habitats are lost to impoundment. Typically, they require a low gradient which allows them to bypass significant barrier heights by controlling the slope and increasing the channel length. However, this requires significant land area. When varying headwater limits the attractiveness or usability of nature-like bypass channels, it can be addressed with a combination of other technical fishways only at the hydraulic inlet (e.g., a single or a few vertical slots at the headwater).

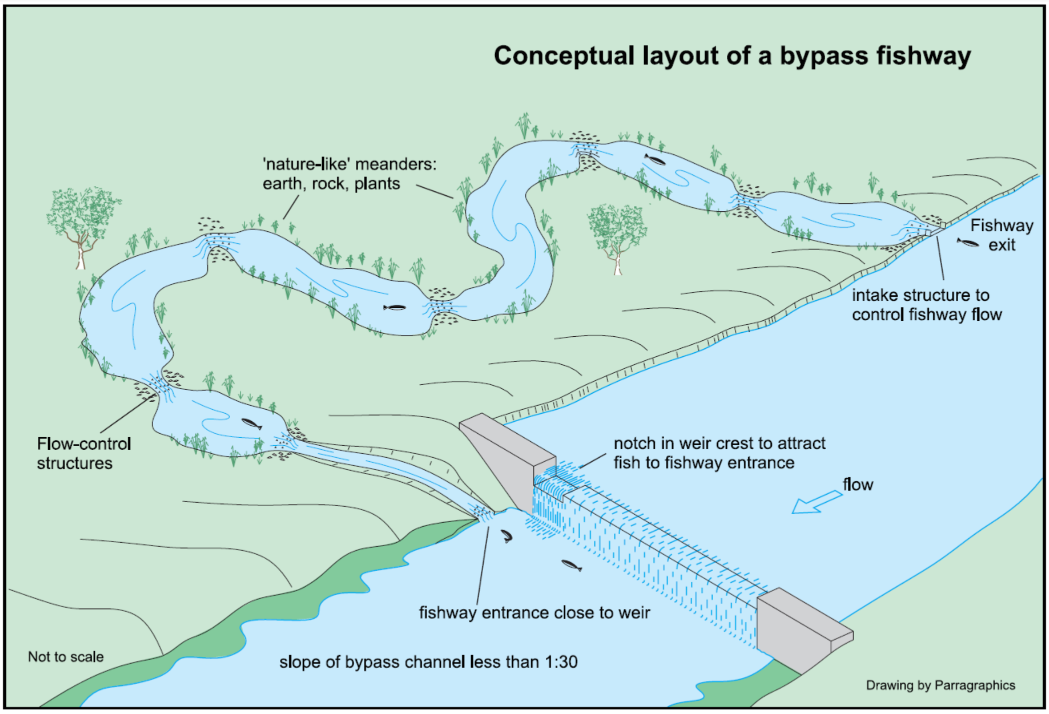

Figure 4.4 ***Concept of a nature-like bypass channel*** (Source: [4.7])

Rock ramp fishways can use all or part of the river channel and use rock placement to provide suitable hydraulics for fish passage. Designs show a range of variations from even to random rock placement (Figure 4.5). Some designs can provide a high degree of hydraulic diversity and riverine habitat. They have limited capability concerning barrier height as the ability of a design to manage slope is generally constrained by the river channel morphology. Emerging technology variants to the rock ramp fishways are **cones** and **hybrid fishways**. The cone fishway uses concrete "cones" at specific space intervals in a concrete channel instead of rocks, resulting in more predictable hydraulics than the original design. The hybrid type uses precast concrete baffles set into a rock-lined channel for the same purpose.

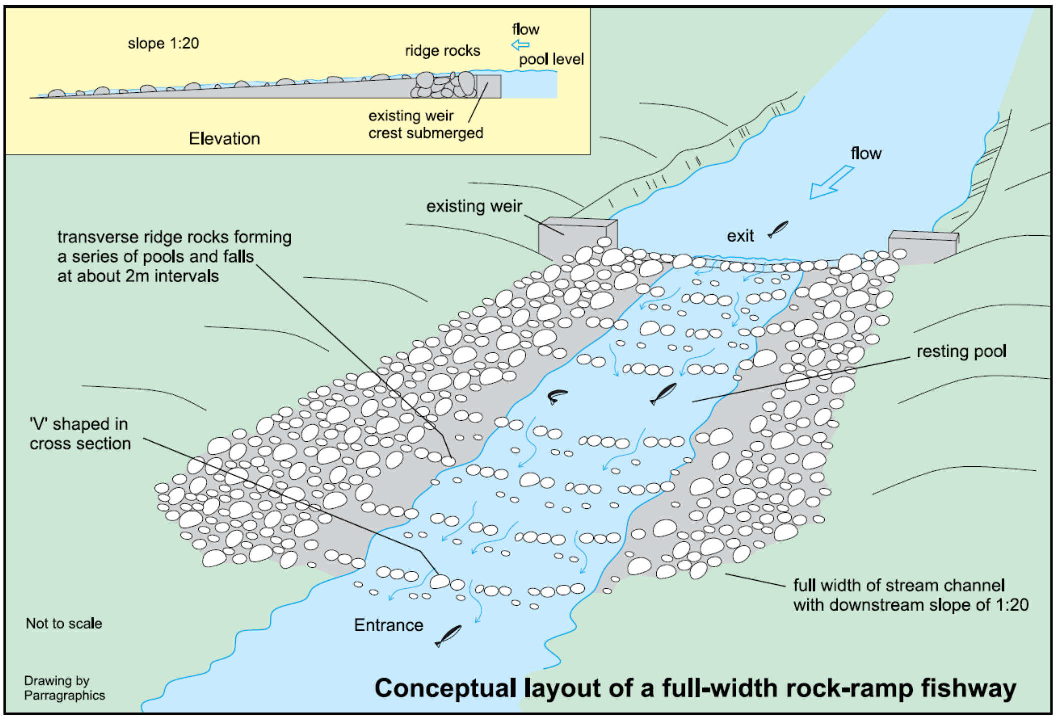

Figure 4.5 ***Concept of a rock-ramp fishway layout over a weir in a smaller stream*** (Source: [4.7])

Fishways for Climbing Species

Passage for climbing species such as juvenile eels (elvers), upstream migrating lampreys, and climbing fish species such as galaxiids requires a specific fishway design that capitalizes on the climbing abilities of these species (Figure 4.6). While appropriate hydraulics play an essential role, the choice of substrate is pivotal to their successful performance. Elver ladders generally consist of a small channel lined with a climbing substrate that provides traction while allowing a small flow to pass. Substrates can include bristles, plastic nodules, and small rocks or pebbles. Ladders can be designed to pass high barriers if resting zones are also assured on the way (up to 30 m high dams). In contrast, other designs convey migrating elvers or lampreys into a cage for subsequent trap and transfer.

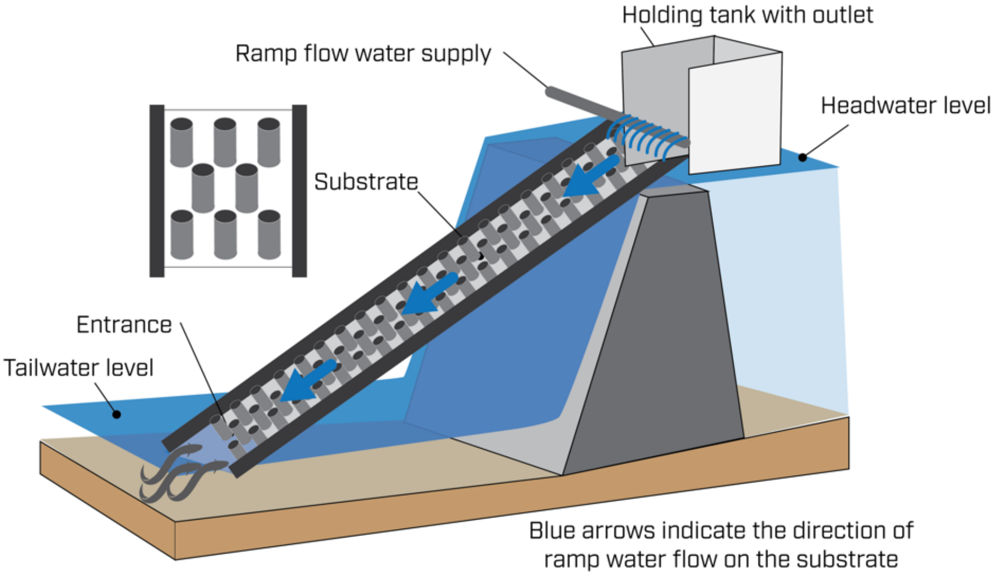

Figure 4.6 ***Illustration of special fishway for climbers***
(Source: SINTEF Energy Research, Norway)

Fish Lifts, Locks, and Pumping Facilities

Various fish lifts and locks have been designed worldwide, both automatic and manual systems. One of the main challenges for each design is efficiently collecting and delivering the fish to the lift, lock, or pump intake. Unlike non-mechanized fishways, fish locks and lifts operate cyclically to trap and transfer fish past considerable migration barriers. Therefore, it is essential to schedule an operation cycle and maintain operation seasonally or continuously according to the ecological importance of migratory fish species.

The primary application for fish locks, lifts, and pumping facilities is sites or applications where the allowable footprint is limited or where the barrier height precludes the use of non-mechanized, channel-style fishway designs. In other cases, they may be suitable for selected species that are heavily affected by large reservoirs. At the same time, such facilities also function as best practices in some cascade hydropower systems.

Fish locks are similar to the approach used to facilitate vessels along inland waterways. Flow attracts fish into the entrance chamber at the dam's base via water releases (Figure 4.7). At the same time, upon closing the gates, it operates water levels at the intermediate chambers until it reaches the same level at the adjacent downstream or upstream level, depending on the sequence order. A range of designs is used depending on the size and characteristics of the dam.

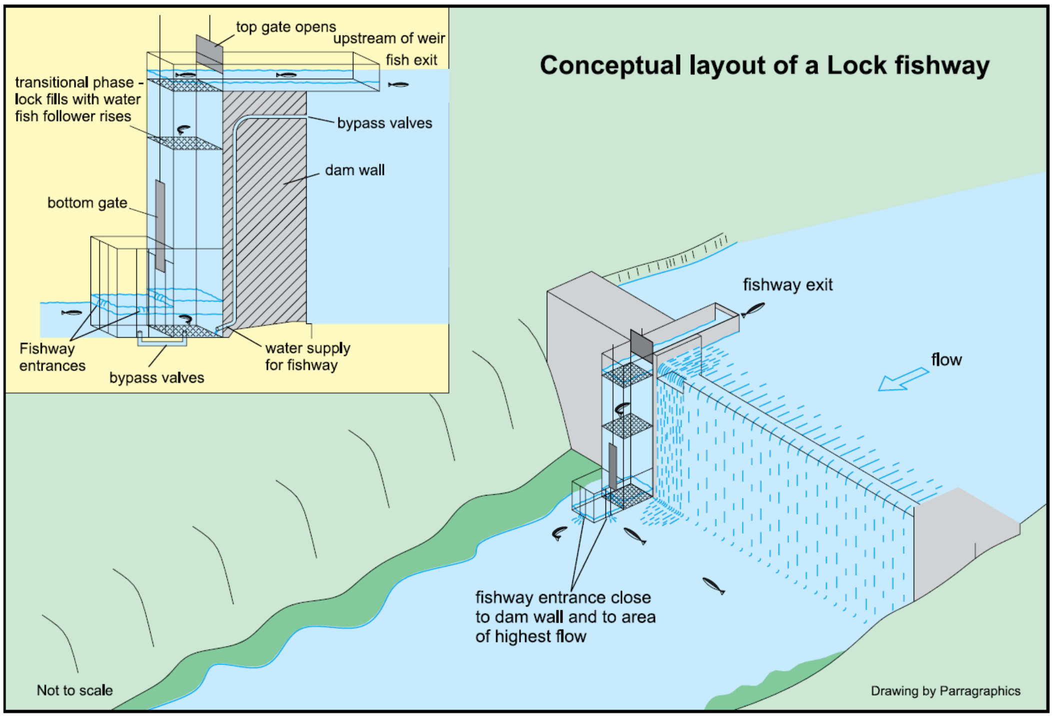

Figure 4.7 ***Concept of a fish lock system*** (Source: [4.7])

Fish lifts (also called fish elevators) utilize a mobile fish hopper conveyed by a hoist to move fish past migration barriers (Figure 4.8). Fish are attracted to the hopper at the dam's base using a proper flow. The hopper is then closed before lifting above the upstream water level. Its contents are then emptied into the upstream waterway. A range of designs is used depending on the structure and shape of the dam.

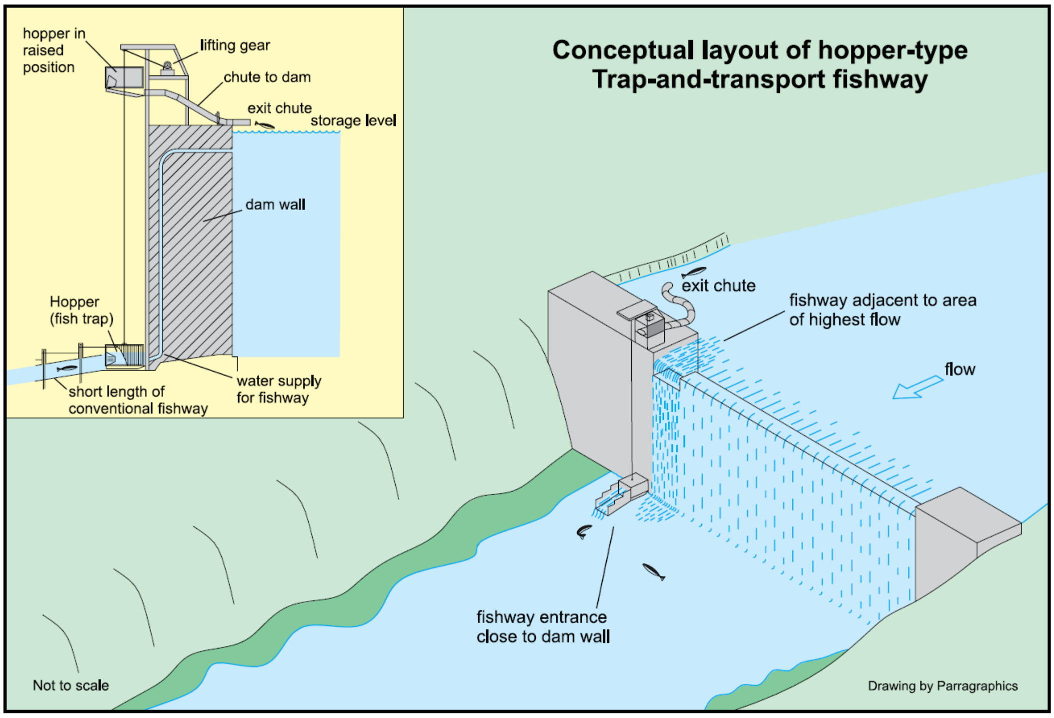

Figure 4.8 ***Concept of a fish elevator system*** (Source: [4.7])

In recent years, **pumping facilities for fish** have been developed in North America[2] and Europe[2] for the fish farming industry and upstream fish passage in rivers. Fish pumps can pass live fish over barriers using pumped water or pneumatic systems to convey fish, and advanced by machine learning techniques; their system can recognize, register, and allow or reject fish passage according to the needs of native species while also capable of excluding invasive species.

Trap and Transport Facilities

The **trap and transport** system (T&T) uses similar principles to other non-volitional facilities, luring and trapping fish in a tank that can be transported to its destination. Depending on the fish species and the distance to travel via trucks or similar, it might be necessary to supply aeration in the fish tanks. T&T systems are acceptable temporary solutions when constructing new or refurbishing existing hydropower plants. In multiple hydropower plants (cascade systems) where volitional measures have very low efficiency or where it is not feasible to retrofit barriers for the upstream migration of fish, T&T may be the only realistic solution. It is essential to design and maintain the system for long-term operation during the facility's life cycle in such a case.

Table 4.1 presents a collection of upstream fish passage facilities with information on their application, advantages, and disadvantages.

It should be noted that the Roadmap helps the reader navigate through the variety of different measures to narrow them down to a few potential candidates. The responsibility for final decisions at a specific hydropower plant should ideally rest with an involved team of experts. Table 4.1 summarizes the key features of the discussed measures based on their advantages and range of application. This table is the basis of the decision-making criteria for guidance in selecting the most appropriate upstream fish pass type, as in Flowchart 2.1. The next sub-section introduces recommendations to optimize upstream passage facilities for fish.

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[2] Disclaimer: links to the commercial developers are provided as the authors believe they represent promising technology, while only a few providers exist in the world to the author's knowledge.

Table 4.1-A ***Overview of the principal fish passage facilities and their general application***

UPSTREAM FISH PASSAGE FACILITIES	GENERAL APPLICATIONS	BENEFITS/ADVANTAGES	BARRIERS/DISADVANTAGES
VOLITIONAL MEASURES (I.)			
Technical fishways: VERTICAL SLOT	- Low- to medium-head applications (<30-40 m).	- Widely used and well-known. - Relatively flexible headwater range. - Design can be adjusted to suit differing channel and fish sizes. - Low maintenance.	- Moderate footprint. - Relatively expensive.
Technical fishways: DENIL	- Can pass benthic species, better suited to fish >40 mm long (slope ca. 1:12) - Low-head applications (<5-10 m).	- Widely used and well-known. - Relatively cost-effective as it can be prefabricated from a range of materials. - Can be used for steep applications with limited space (up to 1:6 slope). - It is more slope tolerant than vertical slot fishways. - Has a relatively small footprint. - Can be suitable for benthic species.	- Design favours larger, strong swimmer fish. - Limited headwater range. - Evidence of poor passage for some surface migrating and smaller fish. - Less recommended in new guidelines.
Technical pool fishways: POOL AND WEIR, including submerged orifice	- Low- to medium-head applications (<30-40 m).	- Simple design. - Widely used. - Wide functioning range but limited effective range.	- Limited headwater range. - Expensive due to concrete channel.
Emerging technology: POOL AND WEIR VARIANT: Trapezoidal weir	- Low-head applications (<2 m).	- Relatively inexpensive. - Prefabricated design. - High and low discharge zones. - High attraction discharge. - Suitable for a range of fish sizes.	- Only suitable for very low-level weirs. - Species applicability is still being established. - Limited headwater range. - Large footprint. - Requires a concrete channel.

Table 4.1-B ***Overview of the principal fish passage facilities and their general application***

UPSTREAM FISH PASSAGE FACILITIES	**GENERAL APPLICATIONS**	**BENEFITS/ADVANTAGES**	**BARRIERS/DISADVANTAGES**
VOLITIONAL MEASURES (II.)			
Nature-like fishway: BYPASS CHANNEL	- Potentially scalable to suit the head.	- Resembles natural stream. - Capable of passing a broad range of species. - Fits into natural surroundings. - Provides riverine habitat. - It can be constructed from local materials. - Not limited by dam height, only footprint size. - Suitable for a range of fish sizes.	- Expensive. - Can have a significant footprint for high dams. - Variable headwater can limit operation unless combined with technical passage types at the hydraulic inlet. - Can require significant flows. - Low slope usually limits the use of such channels to low-head dams or diversion weirs (<1:30 slope).
Nature-like fishway: ROCK RAMP	- Low-head applications (<3-5 m).	- Relatively inexpensive and broad water level operating range. - Partial to full-width entry. - Provides a riverine habitat. - Full width manages wider headwater variation. - Suitable for small fish due to channel roughness.	- Can be maintenance-intensive depending upon the design. - Limited dam size. - Can be limited by variable headwater depending upon the design. - Requires access to large rocks.
Emerging technology: ROCK RAMP VARIANT - CONE	- Low-head applications (<3-5 m).	- Prefabricated baffle. - Relatively inexpensive and easy to construct. - Suitable for small to large fish. - “Formalized” rock ramp with consistent design.	- Only operates above the whole supply level. - Limited headwater range. - Concrete channel required - Less effective for small fish at high flows. - Potentially large construction footprint depending upon the design.
Emerging technology: ROCK RAMP VARIANT – HYBRID FISHWAYS	- Low-head applications (<3-5 m).	- Prefabricated baffle, relatively easy to construct. - Flexible headwater range depending upon design dimensions. - Does not require a concrete channel.	- Requires access to suitable rock for construction. - Can have a significant footprint. - Limited data available on the performance.

Table 4.1-C ***Overview of the principal fish passage facilities and their general application***

UPSTREAM FISH PASSAGE FACILITIES	GENERAL APPLICATIONS	BENEFITS/ADVANTAGES	BARRIERS/DISADVANTAGES
VOLITIONAL MEASURES (III.)			
Climbing species; Elver ladder	- Potentially scalable to suit the head.	- Suitable for juvenile eels, lampreys, and some climbing fish species. - Relatively inexpensive and with low maintenance. - Relatively small footprint. - Can manage variable tailwater heights and can operate independently of headwater levels.	- Species (juvenile eel) specific particularly at large dam heights. - Suitable slope sensitive to substrate selection. - Lampreys can block some designs.
NON-VOLITIONAL MEASURES			
Fish lift/lock/pump	- Scalable to suit the head.	- Suited to a wide range of fish sizes. - Ability to lift fish across any dam size with limited space requirements. - Low footprint. - New technologies are promising based on the first tests.	- Complicated and expensive technology. - Requires power to operate. - It is technically complex. - May require continuous supervision or daily inspection and adequate maintenance.
Trap and transport	- Not limited by the head, applicable for cascade systems.	- Suited to a wide range of fish sizes. - Potential to transport fish across any size or multiple dams, with relatively low capital costs.	- Requires transport infrastructure between the dam's base and upstream impoundment(s). - Labour-intensive, and potentially high operating costs.

4.2.4 RECOMMENDATION FOR UPSTREAM PASSAGE OPTIMIZATION

The Roadmap comments on developing "appropriate" policies to ensure safe passage, where they do not presently exist or are ineffective. Where such policies requiring fishways to be developed exist, the following steps require the systematization of knowledge about the target species' ecological requirements, the understanding of the spatial scale of movements, and the spatial context of the dam in the affected catchment. This information will define objectives and the monitoring programs to evaluate the fishway performance. Next, the design and costs to implement the fishway and monitoring programs would be added to the capital cost of the dam. There will also likely be an additional cost incurred where mitigation measures affect the operation of the hydropower plant. At the end of this process, stakeholders will have a baseline to make well-informed decisions. Seeking a practical solution that provides value at a reasonable cost is an essential component of decision-making.

A wide range of factors must be considered when selecting the most appropriate type of fishway for a site. As mentioned before, these include but are not limited to site characteristics, including barrier size, topography, hydrology, target species or species assemblage and extent of ecological understanding, invasive fish considerations, legislative or regulatory requirements, power scheme operating requirements, and available budget and community requirements. Table 4.1 overviews the principal fish passage facilitation methods and their general application. It is recommended that the solution choice be guided by a team of experienced fish passage specialists familiar with the key factors that must be considered to select an appropriate choice and successful design. Multiple entrances or passage types should be considered for watercourses with highly diverse species to address the various fish species.

Several approaches can be taken to reduce fish's negative stimuli and stressors inside the fishway. Firstly, designs of the internal elements, like baffle profiles or vertical cylinders in the main jet of vertical slot fish passages [4.8], are pivotal and can noticeably affect the turbulent flow field [4.9]. This also applies to the design of resting zones distributed within the fishway. Dimensioning and distribution are dependent on the swimming capabilities of the fish species.

Secondly, the criteria for well-performing measures are to maintain a clear and direct main flow path towards and inside the facility that fish can use while providing adequate resting zones.

Thirdly, fishway entrances need to be attractive and approachable to upstream migrants. Criteria are usually addressed by careful selection of downstream outlets and by sufficient attraction flow rate. Attraction flow (i.e., the component of flow over or through the barrier) is considered as the flow that can lead upstream migratory fish through hydraulic cues towards the downstream entrance of the fishway and within the facility as well towards its upstream entrance. The rate of concurrent flow typically varies between 1 and 5% of the maximum flow discharge through the turbines. Usually, 3 to 5% of the turbine (or power) flow is recommended for small hydropower plants (Q_{prod}< 20-30 m^3/s), while 1-3% is recommended for medium and large power plants. Several measures (Figure 4.9) can increase the attractiveness of the fishways, such as:

A. Multiple entrances for the upstream migratory species (multiple hydraulic outlets) are placed near discovered migration routes for species.

B. The increased flow rate through the fishway.

C. Auxiliary flow is injected at the end of the fishway. The total flow passes through its downstream entrance or entrances.

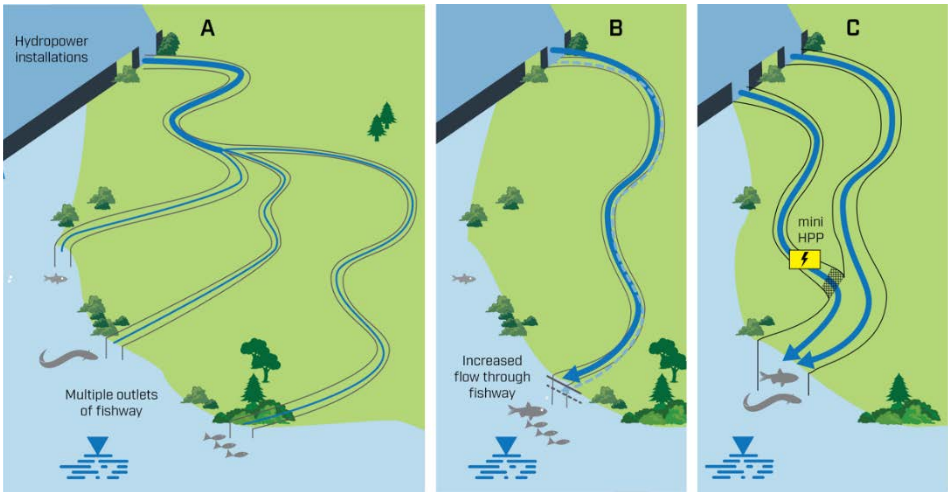


Figure 4.9 ***Illustration of upstream optimization for fishways following the three concepts, such as fishway with multiple hydraulic outlets (A), with the increased flow (B), or the with auxiliary flow with a mini HPP scheme (C)*** (Source: SINTEF Energy Research, Norway)

Case *C* is only recommended when the total flow rate allocated for fish migration cannot pass through the fishway for technical or other reasons.

In any option, a highly turbulent attraction flow can hinder the upstream movement of fish when it is poorly designed or operated, especially with options *B* and *C*. In cases where rapid flow conditions are inadequate for native species, it is even more important to address migratory cues (hydraulic or environmental) towards and within the fishway facilities. To prevent such situations, a reasonable flow rate must be well determined for all conditions (from low- to high-flow period) to match the swimming capability of the ecological target species (Section 2.6). In general, if the species are not excellent swimmers (for instance, trout or salmonids are considered strong swimmers, while cyprinids are often poor swimmers), highly turbulent, "white water" conditions (where TDG levels are high) in the entire water column must be avoided, and flow energy must be sufficiently dissipated in the attraction flow. Moreover, it is necessary to consider any competing flows from main outlet conduits discharging into the regulated river reach. Power flows passing through the turbine or water spilled over or through the dam may hinder attraction flows to fish passages unless their positioning and operation consider these conditions.

4.2.5 DOWNSTREAM FISH PASSAGE FACILITIES

Many fish species that need to pass hydropower plants on their upstream migration path must pass the same facilities during downstream migration (i.e., during one of their life stages). In contrast to the understanding and facilitation of upstream migration measures, means to provide safe downstream passage have not received the same level of research and development. However, it has equal, if not higher ecological importance.

Downstream migratory fish may use the same facility designed for upstream migration. Still, the standard conditions do not attract them into the fishway during their downward journey. Instead, fish continue towards other alternatives with more attractive flow quantities, like water spills at dams or diverted flows through intakes. Unless fish are guided into well-functioning downstream routes, their safe passage is not guaranteed, especially when they continue through headrace conduits. Indeed, it is a challenging task to prevent fish entrance into the turbine intake. Still, it is possible to separate downstream migratory fish successfully from the diverted flow with new knowledge and technology. While there is no general recommendation on suitable measures for all cases, like upstream fish passage facilities, the final design of downstream measures should incorporate site- and species-specific requirements following regular maintenance and monitoring. Additionally, downstream fish passage facilities can be retrofitted to existing power plants. Still, successful solutions will commonly be most cost-effective when included in the planning phase of new projects.

Downstream fish passage facilities are differentiated into screening (or shielding) measures combined with guidance to a bypass system and conveyance measures (Figure 4.10). The latter does not separate fish from diverted flow utilizing civil works. They either allow fish movement through special turbine units, which by design and operation cause less harm to pass fish or convey them towards other alternatives by operational measures. The former separates fish from the diverted flow, using appropriate design, maintenance and operation means; screening is based on a physical or behavioural barrier for migrating fish, where they are guided into a bypass channel suitable for fish passage or are collected in a system that transfers them expeditiously below the dam.

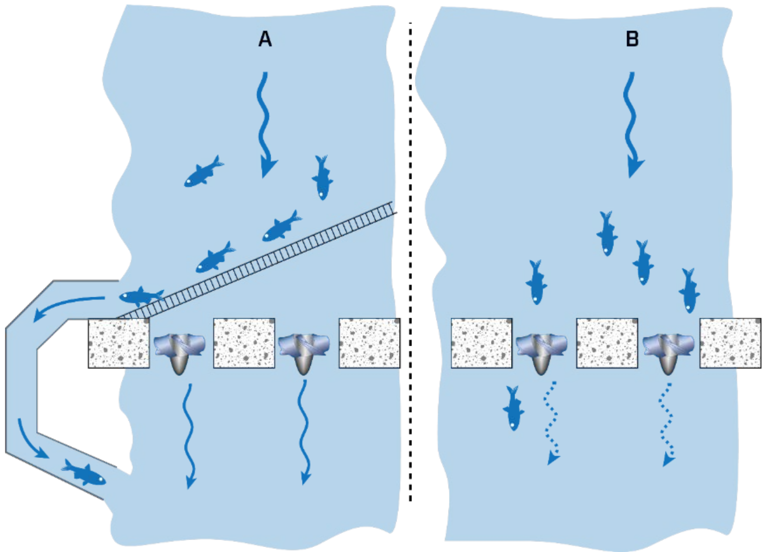


Figure 4.10 ***Conceptual illustration of screening (A) and conveyance (B) measures***
(Source: SINTEF Energy Research, Norway)

Table 4.2 presents a variety of commonly used protection measures based on the preceding principles. In contrast, Table 4.3 summarizes their key features, including their advantages and range of application. The general guidance for the selection of downstream fish passage solutions is found in Flowchart 2.2.

For an extensive demonstration of the measures, the reader is advised to check the **Appendix** (available separately), while more in detail information on all of the technologies is given in [4.10][4.11][4.12].

Table 4.2 ***Fish protection and guidance technologies for downstream fish migration past HPPs***

DOWNSTREAM FISH PROTECTION TECHNOLOGIES AT HYDROPOWER FACILITIES					
SCREENING/SHIELDING AND GUIDANCE				**CONVEYANCE**	
Physical Barriers	**Mechanical Behavioural Barriers**	**Sensory Behavioural Barriers**	**Collection Systems**	**Ecologically Improved Turbines****	**Ecologically Improved Operation****
- Fine screens - Rotary screens - Eicher screen - Modular inclined screen - Barrier nets - Coanda screen - FGRs* with narrow bar spacing (angled/inclined)	- FGRs with wide bar spacing (louvres, angled bar racks, curved-bar racks) - Skimming walls/bottom overlays	- Light (strobe/ mercury) - Low-frequency sound - Electricity - Air-/water curtains	- Barrier nets - Surface collection pipes - Travelling screens - Fish pumps - Trap and Transport	- Alden - Minimum Gap Runner - DIVE turbines - Restoration Hydro Turbine - Very Low Head	- Early warning systems - Weir/spill overflow - Navigation lock passage - No partial load operation for conventional turbines
	- Hybrid barriers (combination of physical and behavioural barriers)				
Bypass					

*FGR = Fish Guidance Rack / ** Ecologically Improved Turbines and Operation are used to describe ways to reduce the impacts on fish passing through turbine passageways or convey them towards other alternatives by operational measures.

Ecologically Improved Turbines

Research, testing, and studies have guided on ways to improve turbine design and operation, intending to minimize potential sources of injury to which fish may be exposed. They are often entitled "fish-friendly," but labelling them as **Ecologically Improved Turbines (EIT)** is more appropriate since fish mortality can never be reduced to zero.

Future research should better investigate the fish-turbine interaction by artificial fish replicas and by field studies that monitor the survival, mortality, and fitness of real fish entrained through EITs. Some limitations of EITs are that mortality can never be reduced to zero [4.13]. However, it can approach zero under given conditions. It must be noted that such investigations may be carried out by combining various techniques to minimize the negative impact on passing fish (e.g., hydrodynamic simulations and biological response models, among others [4.14]). In general, the environmental performance depends on the entry point of fish and the need to avoid fish entering the turbine under high-head conditions, where the pressure gradient may be dangerous despite the ecological design of the turbine. **Therefore, passage through turbines alone is not recommended as best practice; rather, an EIT can be a complementary solution with other measures if the prevention of fish passage through the turbines is not achievable due to economic, geographical, or other reasons.**

The types of turbines identified with improved ecological performance include Alden and modified Kaplan units with a vertical axis and bulb setups with a horizontal or inclined axis [4.15][4.16]. Furthermore, self-aerating and oil-free turbines also have slightly better ecological performance than conventional designs, providing improved downstream water quality from aeration services and reducing risks of oil spills and pollution. Even though they are not considered EIT for fish passage, they can mitigate other negative impacts of hydropower development; thus, brief information is presented at the end of the section.

The present design of the **Alden turbine** (Figure 4.11c) has reduced the number of blades to three. It has changed the geometry of the blades for thicker leading edges wrapped around the vertically rotating shaft, which has been demonstrated to reduce fish mortality. The speed of rotation is slower compared to conventional turbine technologies. The technology can be considered an improved ecological version of the Francis turbine; however, it has not yet been proven at a prototype level due to some challenges to overcome before it is ready for commercial deployment. The presented concepts of the Alden turbine contribute to ecologically improved designs.

Recent developments of the Kaplan turbine have resulted in different variants, which are presented below. Overall, studies report improved survival rates with such types compared to the conventional Kaplan (Figure 4.11a). The **Minimum Gap Runner** design (MGR) reduces the gaps between the adjustable runner blades, the hub, and the discharge ring (Figure 4.11b). MGR turbines normally use between 10 and 40 m hydraulic heads and flow above 17 m^3/s [4.17][4.18]. While they have incurred higher development costs than a Kaplan turbine, full-scale demonstrations have verified their performance with improved fish survival rates and increased efficiency than conventional designs [4.17].

As for the technology of the **DIVE turbines**, the double regulation is provided by the controlled rotational speed rather than by the runner blade pitch. Such an approach allows the turbine to maintain the blades in their maximum opening position, thus reducing the strike probability with fish and avoiding dangerous gaps between the blades and other parts of the machine. The **Restoration Hydro Turbine** is a compact unit with a short draft tube, which can be installed at a range of settings from retrofit to new systems with 2m to 10 m head. The **Very Low Head (VLH)** unit is adapted to sites with <5 m head to work in an axial flow mode, with fixed runner blades and adjustable rotational speed.

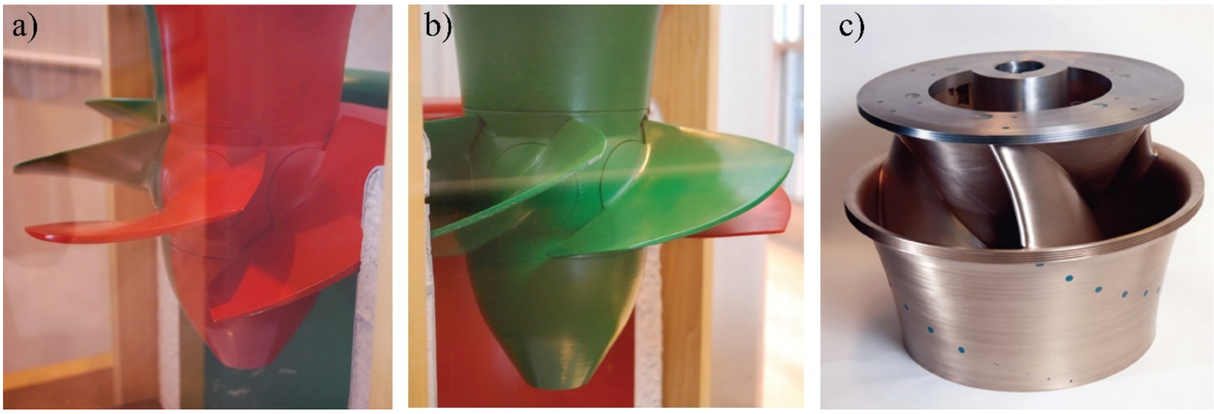


Figure 4.11 ***Kaplan (a), MGR (b), and Alden (c) turbines*** (Source: Grant County Public Utility District)

Self-aerating turbines are also being developed because the water in the lower zones of many reservoirs is often oxygen deficient. The discharge of this water can cause damage to downstream ecosystems (see Section 3.2.4). Therefore, an aeration solution allows atmospheric air to be drawn naturally into the aerating hollow runner blades. This technology maximizes bubble distribution in the draft tube and tailrace while minimizing the impact on the turbine. Capital costs for the aeration systems are generally less than 8% of the total turbine costs, with no additional efficiency or capacity loss when the aeration systems are not operational [4.19].

Oil-free turbines are based on conventional designs. Commonly older or smaller Kaplan turbines tend to be upgraded to remove oil from the turbine hub. In contrast, Francis' designs have fixed blades that do not require oil in the runner hub. Scientific investigation explained that oil leakage from hydro turbines negatively impacts the environment and can cause operational and maintenance problems [4.20]. The cost of an oil-free Kaplan runner may vary by 5-10% greater than a traditional runner because of the self-lubricated bushings and stainless-steel parts. However, cost savings occur because fire protection is unnecessary, and fewer auxiliary systems are required.

Self-aerating and oil-free turbines have the same application range as analogous turbines.

Further information on fish turbine passage, comparison of various turbines, turbine mortality assessment, and recent findings are presented in FIThydro Deliverables 2.1 and 2.2.

Ecologically Improved Operations

Early warning systems, weir overflow, i.e., spilling for fish passage, navigation lock passage, and avoidance of partial load operation are **ecologically improved operational measures** to reduce impacts of turbine passage or avoid fish passage through the turbine chambers providing a safe corridor for downstream fish migration.

Preventing fish from entering hydropower intakes is important under normal flow conditions since most flows are diverted through the turbine for hydroelectric generation, and fish generally follow the main discharge route. Passage through turbines can be reduced by **total or partial turbine shutdown** and fish passage over **weirs or spillways or through outlet discharges**; however, this reduces power generation and revenue during flood periods (FIThydro Deliverables 2.1). For this to be effective, it is also necessary to have an appropriate spill bypass design, as fish are more likely to be attracted to this bypass if it is close to the power intakes.

Kaplan turbines are often operated under partial load when power flows are reduced, or electricity demand is low or variable. Under this mode, fish mortality will likely increase. To reduce fish mortality, partial load operations of conventional turbines should be avoided, if possible, during fish passage through the turbines. The more turbines installed in a powerplant, the easier it is to avoid or minimize partial load operation by generating fewer turbines at full load. However, in many areas, hydropower production is increasingly called upon to balance the variable generation from solar power and wind energy. This can harm fish and riverine ecosystems.

The use of **navigation locks for fish passage** is limited because the specific lock operating regime may be incompatible with the fish migration period and due to unfavourable flow conditions at the inlet and outlet of the lock. By addressing these issues (providing attraction flow to lure fish and release them downstream, in addition to fish-specific operations), navigation locks can be used, although generally recommended as complementary measures to other downstream fish passage methods (FIThydro Deliverables 2.1 and 2.2).

Early warning systems can be based on water quality sensors, e.g., DIDSON sonars, MIGROMAT, or other sensors to detect mass fish migration or indicators for it and alert the hydropower plant operator to operate in a fish-friendly mode [4.21]. In some cases, this may require the termination of power production during key migratory periods.

Physical Barriers

Various **physical barriers** block fish of many sizes from entering the turbine units. **Fine screens**, e.g., flat plate screens (Figure 4.12), submerged bar screens, and **rotary screens** are used as total fish exclusion with a low bar spacing < 4 mm and a porosity < 27% and relative low design approach flow velocities < 12 cm/s [4.12]. In addition, **Eicher screens** and **Modular Inclined Screens** are used to exclude fish from turbine intakes or penstocks and guide them to a bypass.

Figure 4.12 ***Vertically inclined flat plate at the Little Wind River in Wyoming, USA***
(Source: OneFish Engineering LLC)

Coanda screens (Figure 4.13)**,** **classical bottom-type intakes, and Lépine/Tyrolean-type water intakes** are used in mountainous regions with high sediment transport to extract water for hydropower ([4.12] and see FIThydro Deliverables 2.1). In each case, the flow tops the crest of the structure, where the intake is located under the downstream slope. Due to their design, fish (and debris and sediments) are separated from the flow. Their satisfactory performance requires small bar openings to avoid fish passing through or between the bars, minimum flow depths at the bottom toe of the screen to prevent injuries, and enough water head during low flow periods. Applications of these screens are limited to relatively small unit discharges (<10 m^3/s).

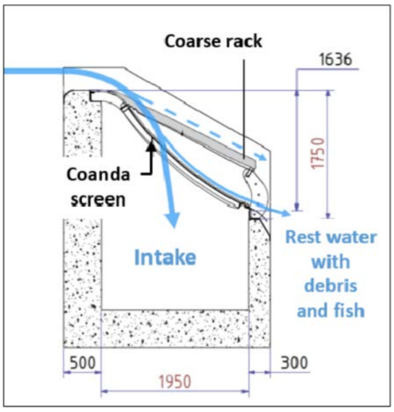


Figure 4.13 ***Schematical side view of the Coanda intake***
(Source: FIThydro.wiki)

Another approach to exclude fish from moving through a power intake or into an intake is to use custom-designed, flexible exclusion and guidance nets, i.e., **barrier nets** (Figure 4.14). These nets work like an extension of the shoreline, excluding fish from attempted passage through the turbines and guiding them into a bypass system to safeguard them downstream. Alternatively, the collector facility could be combined with a floating surface collector. In this option, fish are held in the collectors in specially designed tanks for further transport by some methods (e.g., truck and elevator, among others). It can be combined with data collection in all cases. To date, this approach has been successful in providing a considerable improvement in downstream migration rates. Limitations relate to mesh and fish size and maintenance.

Figure 4.14 ***Rendition of complete guidance net at upper Baker Lake, Washington State, USA***

Fish Guidance Racks (FGRs) with an adjacent bypass system are promising technical solutions for downstream fish migration at power plants. They can be classified as physical barriers when FGRs are equipped with narrow bar spacing and behavioural barriers when constructed with wide bar spacing based on their primary technique to prevent fish passage into the turbine chamber through power intake.

FGRs with Small Bar Spacing are considered a physical protection and guidance barrier for a specific size of fish species with their 10 to 30 mm bar spacing. Following recent studies and applications, such structures with horizontal bars and a bypass system provide effective protection and guidance for HPPs with $Q_{prod} < 120$ m^3/s [4.22]. Another variant of these FGR designs is the angled bar racks configuration with narrow bar spacing combined with a bypass system at the downstream end. They are placed in front of the turbine intakes at a horizontal angle between 30° and 65° [4.23][4.24] (Figure 4.15a).

Another FGR configuration with small bar spacing for small-to-medium size HPPs is the vertically inclined bar racks with a top bypass system ([4.25][4.26] and FIThydro Deliverables 2.1 and 2.2). Such designs are placed in front of turbine intakes with a recommended vertical angle of 25° (Figure 4.15b).

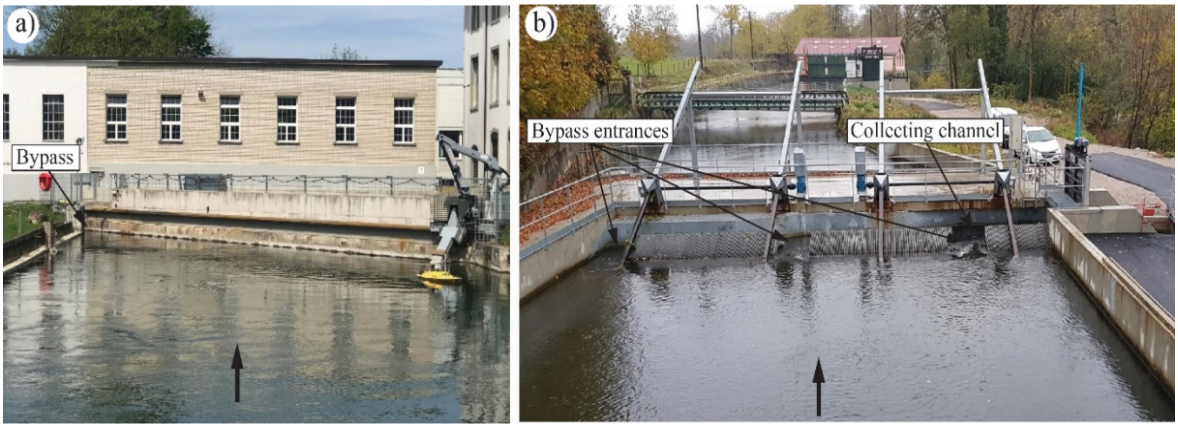


Figure 4.15 ***Horizontal Bar Rack-Bypass System at HPP Stroppel on River Limmat in Switzerland [4.24] (a) and Vertically Inclined Bar Rack-Bypass System at HPP Las Rives in River Ariége in France (b)*** (Source: Ismail Albayrak)

Mechanical and Behavioural Barriers

FGRs with Wide Bar Spacing are classified as **mechanical and behavioural barriers** and developed mainly on RoR HPPs and water intakes with large design discharges. These configurations also guide fish to a bypass with hydrodynamic cues created by the bars instead of physically blocking fish from a water intake. When approaching the rack, fish should perceive the elevated pressure and velocity gradients around and between the bars. This results in avoidance behaviours to proceed further toward the turbines. The velocity component parallel to the rack guides the fish toward the bypass at the downstream end of the FGRs. FGRs with wide bar spacing are called louvres, angled bar racks, modified angled bar racks, and curved-bar racks. They are placed across an intake canal or upstream of the water intake at a horizontal angle to the flow direction of typically 15° to 30°. Efficiency may be limited to a range of flows for some types, which shall be considered during design. The technical differences are shown in Figure 4.16 and discussed in the literature [4.12][4.27][4.28][4.29].

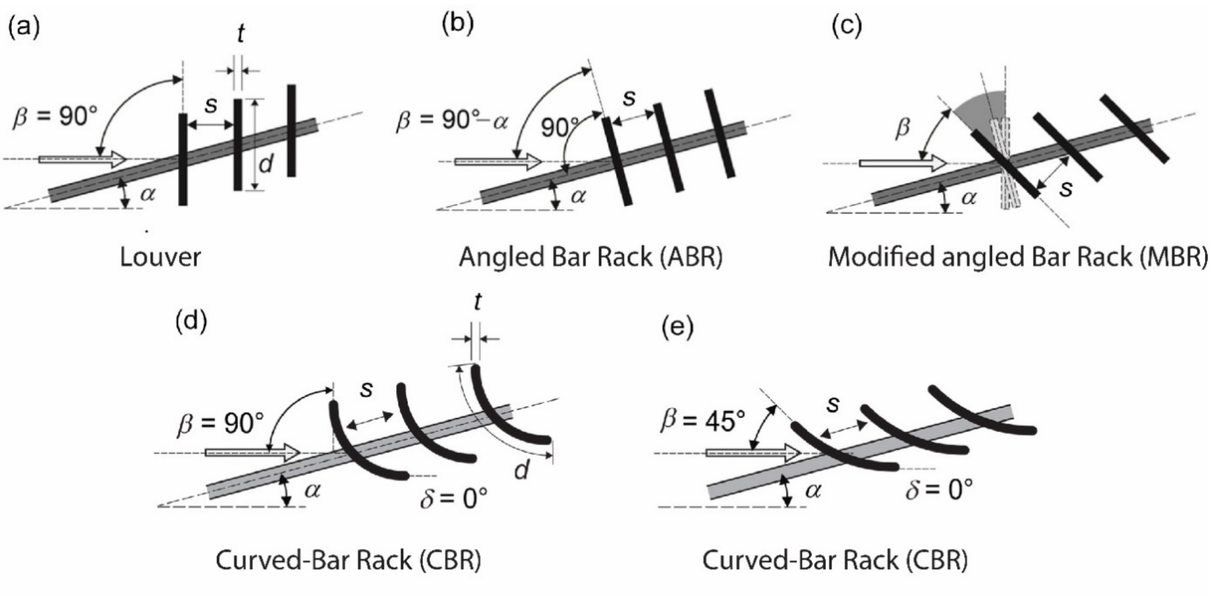


Figure 4.16 ***Technical layouts of different Fish Guidance Racks with wide bar openings (a) Louver, (b) Angled Bar Rack, (c) Modified angled Bar Rack and Curved-Bar Racks with an upstream tip angle of (d) 90° and (e) 45°.*** (Source: [4.29])

Skimming walls block fish's movement near the water surface (down to a few meters below). They are commonly located further upstream of the intake entrance. The good efficiency of such measures is limited to surface-oriented species during their migration (e.g., Atlantic salmon smolts). Skimming walls can be configured as fixed or floating. However, they must be installed at an angle and combined with safe passage alternatives at their downstream end (e.g., with bypass or weir overflow).

Sensory and Behavioural Barriers

Guiding fish by **sensory or behavioural barriers** can be facilitated by various technologies and techniques. In contrast to screening systems, such manipulation aims to repel fish from intake flow and/or attract fish to a bypass corridor without physically blocking the power intake. This means that passage through the turbines should be significantly reduced but not likely to be eliminated. Repelling systems include flashing **lights** (Figure 4.17a), **infrasound devices** (Figure 4.17b), **electricity fields** (Figure 4.17c), **air curtains**, or combinations of such technologies [4.12][4.21]. Alternatively, the electrification of FGRs could represent promising additional protection [4.30][4.31]. Such solutions represent promising additional protection; however, it should be noted that the performance of such techniques is questionable as an only on-field application unless the conditions are like the ones in the successfully reported cases. Hence more studies are needed to discover the potential and limitations of the different techniques.

Figure 4.17 ***Variation of Sensory and behavioural measures on the field and in lab conditions. It presents LED lights for repelling fish at intakes (a), an Infrasound "canon" for repelling fish (b), and an Electrified Curved-Bar Rack – Bypass System (c)*** (Source: [4.31])

There are already projects in practice in which mechanical barriers are combined with a behavioural barrier (low-intensity electric current). These systems can be described as **hybrid barriers** (Figure 4.18). The spacing of the bars (vertical or horizontal) or steel cables (horizontal only) of the mechanical barriers is several centimetres (e.g., 6 cm to 10 cm)[4.32].

Figure 4.18 ***Illustration of hybrid barriers to guide the fish to a nearby bypass (visible in the upper left corner). The horizontally tensioned steel cables only serve to protect fish and can be completely laid down on the riverbed for cleaning and flood discharge***
(Source: Markus Auflager)

Electrification occurs via electrodes fixed to the bars (Figure 4.19) or the steel cables (Figure 4.18). The system can be used to either guide the fish (for example, by placing the steel cables, which can be up to 100 m long, at an angle in the headwaters of the intakes) or only to keep them away (for example, by retrofitting an existing trash-rack with electrodes)[4.33]. Through this system, it is possible to realize functioning fish protection at the distance of the mechanical elements (bars or steel cables) of several centimetres resulting in a significantly low head-loss.

Figure 4.19 ***Illustration of installed electrodes on an old trash-rack within a hydropower intake*** (Source: Markus Auflager)

Bypass Systems

Screening and shielding measures for downstream fish passage offer safe route alternatives through bypass systems. Fish are more likely to be attracted to this bypass if it is close to the power intakes. Guiding fish past intakes requires extensive and site-specific knowledge of the infrastructure, hydraulic conditions, and fish behaviour. Ultimately, successful fish bypass schemes depend on monitoring fish migration. This is particularly important if a water spill is needed since bypass success is often related to the magnitude and timing of spill water discharge [4.34].

When fish approach the physical, mechanical, or sensory barriers, they should be able to perceive the hydraulics cues (i.e., elevated pressure and velocity gradients), which repel them from the intake flows and guide them towards bypasses [4.35][4.36]. Besides, in bypass design, multiple entrances in the collecting channel increase bypass attractiveness (FIThydro Deliverable 3.4).

Collection Systems

Collection systems use similar principles, as discussed, for upstream fishway facilities. They guide the approaching fish into a facility from which fish are transported downstream.

Fish pumps, lifts, and **T&T systems** can be used similarly for upstream fishway facilities.

Surface collection pipes work with various downstream fish diversion and collection techniques (e.g., juvenile bypass systems, floating surface collectors) to re-route fish away from turbines, delivering them safely downstream of the dam.

Travelling screens are continuously moving screens that filter and remove debris and fish from water intakes (Figure 4.20). Fish are discharged into their environment, and debris is collected for future disposal. These fine screens partially cover the turbine intake, and their operation is complex with many technical challenges.

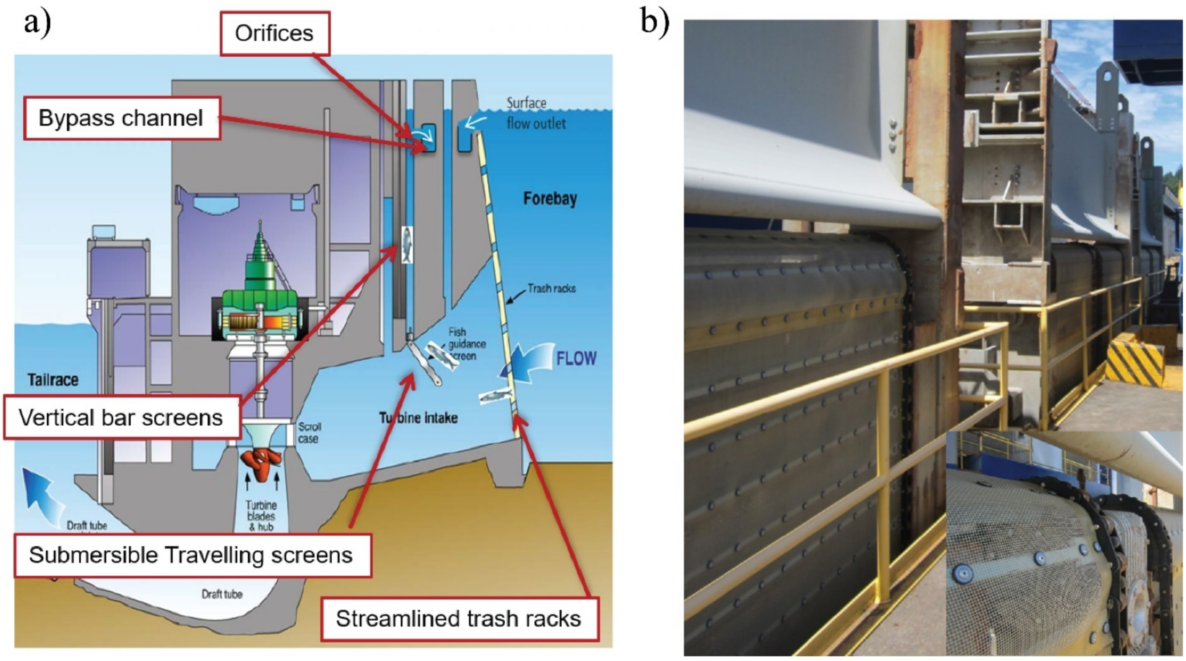


Figure 4.20 ***Illustration (a) and photo (b) of a juvenile bypass system with travelling screens***
(Source *a*: U.S. Army Corps of Engineers; *b*: Ismail Albayrak)

Table 4.3 presents a collection of downstream fish passage facilities with information on their application, advantages, and disadvantages.

It should be noted that the Roadmap helps the reader navigate through the variety of different measures to narrow them down to a few potential candidates. The responsibility for final decisions at a specific hydropower plant should ideally rest with an involved team of experts. Table 4.3 summarizes the key features of the discussed measures based on their advantages and range of application. This table is the basis of the decision-making criteria for guidance in selecting the most appropriate downstream fish pass type, as in Flowchart 2.2. The next sub-section introduces recommendations to optimize downstream passage facilities for fish.

Table 4.3-A ***Applications of the various types of downstream fish passage facilities***

DOWNSTREAM FISH PASS FACILITIES	SUITABLE SPECIES	BENEFITS/ADVANTAGES	BARRIERS/DISADVANTAGES
CONVEYANCE SYSTEMS			
Ecologically Improved Turbines	- Better performance for smaller and juvenile fish.	- All flows can pass through the powerplant. - No need for fish screening systems in front of intakes or a fish bypass system.	- High mortality rates with larger fish. - Higher cost for ecologically improved turbines. - Limited to low-head dams (up to 15-30 m).
Ecologically Improved Operations: EARLY WARNING SYSTEMS NAVIGATION LOCK PASSAGE HPP OPERATION	- All types of fish species.	- No need for fish screening systems in front of intakes or a fish bypass system.	- May terminate power generation during the key migration period. - No partial load operation and full turbine shutdown cause revenue losses. - Weir or Spillway and attraction flow to navigation locks cause hydropower generation and revenue loss. - Hydraulics and the design of many existing spillways and weirs may not favour fish passage.
Ecologically Improved Operations: FISH PASSAGE VIA SPILL AND WEIR OVERFLOW	- Various, more suited to robust species and life stages. - Better suited to low-head dams.	- Minimal capital outlay, potentially high attraction flow.	- Suitability depends upon species stress tolerance, dam design (e.g., dam height, spillway design, tailwater depth), and the potential for revenue loss.
Collection systems	- Wide range of catchable species.	- Low capital cost, no constrain by power station head. - Ability to closely monitor fish.	- High operating and labour costs.
SCREENING/SHIELDING AND GUIDANCE SYSTEMS (I.)			
Physical Barriers: FINE SCREENS	- All types of fish species.	- Potentially a complete barrier to prevent passage through the turbine. - Well-designed bypass systems provide high migration efficiency. - Barrier nets: high success rate with a side benefit of debris reduction at the trash-rack (reducing head-loss) and reducing operating and maintenance costs.	- Screens blocked by debris increase head-loss. - During retrofitting facilities, bypassed flows cause hydropower generation and revenue loss. - High costs for screens and potential operational issues due to debris clogging at large hydropower plants.

Table 4.3-B ***Applications of the various types of downstream fish passage facilities***

DOWNSTREAM FISH PASS FACILITIES	SUITABLE SPECIES	BENEFITS/ADVANTAGES	BARRIERS/DISADVANTAGES
SCREENING/SHIELDING AND GUIDANCE SYSTEMS (II.)			
Physical Barriers: **FISH GUIDANCE RACKS WITH NARROW BAR SPACING**	- All types of fish species.	- Potentially an almost complete barrier to prevent passage through the turbine.	- Racks with narrow bar spacing can be blocked by debris, resulting in high head-losses and operational issues. - In retrofitted cases, bypassed flows cause hydropower generation and revenue loss. - Not suitable for large HPPs due to velocity limitations for fish injuries and potential operational issues due to debris clogging. - Do not provide total fish protection, as fish smaller than the bar opening can pass through the rack.
Mechanical and behavioural barriers: **FISH GUIDANCE RACKS WITH WIDE BAR SPACING** **SKIMMING WALLS**	- All types of fish species.	- They operate with higher approach velocities than FGR with narrow bar spacing and fine screens, reducing overall structure size and cost. - Less prone to debris blockage (operational advantage) - Depending on the type, they offer high protection and guidance efficiencies for small to large fish species. - Some recently developed curved bar rack-bypass system provides higher fish protection and guidance efficiencies at low head-losses and uniform turbine flow (less impact on hydropower production).	- In retrofitted cases, bypassed flows cause hydropower generation and revenue loss. - High head-losses for louvres. - They may not be absolute fish barriers. - High fish protection and guidance efficiency of modified bar rack-bypass and curved bar rack-bypass systems have been proven in laboratory conditions. Prototype tests for both designs are ongoing in Norway and Switzerland.
Hybrid barriers	- All types of fish species.	- Potentially a highly effective approach to prevent fish passage through turbines (even for small fish).	- Suitable pulse generator is required. - Corrosion of the electrodes must be limited effectively or prevented.
Sensory, Behavioural Barriers	- Studies are available on eels, salmonids, trout, and graylings.	- Can reduce bypass flows and hence loss of generation and revenue. - Cost and maintenance are relatively low.	- Their effectiveness depends on fish species and hydraulic conditions. - More laboratory and field studies are needed.

4.2.6 Recommendation for Design and Optimization of Downstream Passage Technologies

While there is no general recommendation on suitable measures for all cases, the design of a downstream fish passage measure (Tables 4.2 and 4.3) for an HPP requires detailed site- and species-specific information, irrespective of whether it is a high- or low-head dam. Such information can be obtained from construction plans and measurements on-site [4.37]. It is recommended to:

A. Identify and utilize fish migration corridors using radio telemetry or acoustic telemetry techniques at the site.

B. Consider the behaviour and biomechanical properties of target fish species.

C. Match the hydraulic conditions of measures according to the fish species identified preferences from points *A* and *B*.

To assess point (III) velocity and bathymetry measurements using advanced techniques, such as ADCP, should be conducted as shown in Figure 4.21. Based on such data, a physical or numerical model of the HPP can be constructed[4.38]. With any model, positioning and geometric optimization of the measure can be done. Finally, it is recommended to integrate the HPP's operating conditions and the studied site's hydrological boundary conditions and to maintain and monitor the measure's effectiveness regularly.

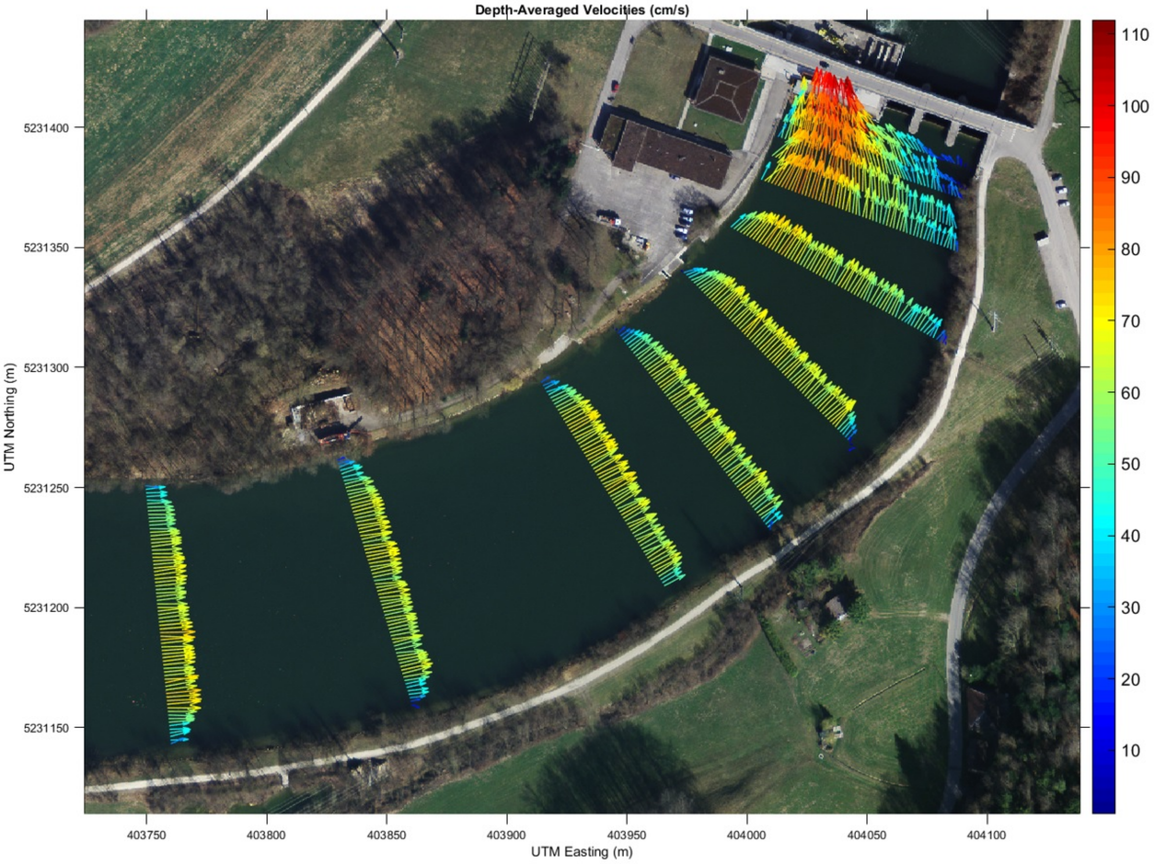


Figure 4.21 ***Exemplary depth-averaged velocity fields [cm/s] upstream of HPP Bannwil, Switzerland, measured with boat-mounted ADCP at a discharge of ~400 m^3/s***
(Source: FIThydro Deliverables 2.2)

During the operation, velocity measurements and fish monitoring are recommended to evaluate the effect of the fish passage measure on the flow field and its fish protection and guidance efficiencies under different load cases at the HPP). Further measure optimization should be made based on the monitoring results. For example, the fish and hydraulic monitoring programs may show that a fish guidance rack efficiently guides fish (i.e., good fish protection and guidance towards the bypass direction). However, fish do not use the bypass because of its unfavourable flow conditions (i.e., the rapid flow velocity increase or increased turbulence). Therefore, the bypass hydraulics must be improved by changing their operation regimes or optimizing their geometry. Similarly, other fish passage measures can be optimized. Overall, hydraulic and fish monitoring at the fish passage facility is most important for performance evaluation and further optimization.

Fish ladders for upstream migration are generally unsuitable for downstream migrating fish because fish tend to follow the main river flow, i.e., the flow running through the turbine. Downstream migration facilities should be designed, if possible, adjacent to those for upstream migration (FIThydro Deliverables 2.1 and 2.2; [4.12][4.25][4.39][4.40]) or at an alternative location that maximizes attraction to the fishway, i.e., the intake channels. Accordingly, screens and bar racks can be placed upstream of the turbine or at the entrance of the intake entrance channel to prevent fish entry and guide them towards the bypass. However, one potential trade-off is that these screens may induce additional head-losses, reducing the power output of the hydropower plants. Meanwhile, more ecologically improved turbines can be installed to work with migration facilities and reduce fish mortality. However, they leave a residual mortality risk. Their use is generally only applicable in RoR sites with heads below 15-30 m. At high-head dams, collection systems may be the only choice as best practice.

For downstream migration, inclined and angled (oriented) bar racks have been studied and optimized to improve fish protection and guidance for fish. In most hydropower projects, either bar racks or barrier nets are commonly recommended as best practices. To choose between the different types of measures, the reader is directed to follow Flowchart 2.2 in Section 5. After implementing any measure, further monitoring is recommended, as discussed above, to evaluate and, if necessary, optimize these measures to improve performance.

4.2.7 TAILRACE

Flows through the tailrace may attract fish migrating upstream or allow entry of resident fish into the draft tube. In either case, such situations will likely harm fish populations. The extent of impacts and the need for mitigation measures depend on the fishes' biological factors and physical characteristics at each site [4.41].

It is essential to design, locate and operate fishways suitable for each fish species to provide suitable attraction flows and locations, even when flow through the tailrace is at full or near full load operation. However, the associated high flow velocities will likely prevent fish from entering the draft tubes. On the other hand, low velocities may allow migratory and resident fish to enter the draft tube during partial operation or shutdown. In that case, they may suffer a severe or lethal injury during the subsequent unit ramp-up or start-up. For this purpose, tailrace barriers are available to prevent fish entrance into the draft tubes. The same techniques can usually be applied at the draft tube outlet selected for the intake channel for downstream migrating fish (see Section 4.2.5 for information on screening/shielding or sensory/ behavioural barriers).

4.3 Impoundment

Impoundment as a physical consequence of damming a free-flowing river is linked to multiple processes which alter the local biotic and abiotic environment on many levels. They are addressed in different sections of this document, whether the consequence of inundation is related to the backwater effect upstream (Section 4.3), sedimentation (Section 4.4), changes in water temperature and quality (Section 4.5), or flow regulations due to hydropower utilization (Section 4.6).

Compared to RoR systems, storage hydropower poses more significant changes and challenges to the riverine environment. The consequences of impounding a watercourse are complex, and so are the solutions. In comparison with natural lakes, the residence time of water is usually shorter in reservoirs, which can be beneficial for water management. Environmental objectives at dammed watercourses may be addressed efficiently by implementing and operating multiple facilities. They can consist of several units of the same type or a combination of different facility types. The Roadmap introduces the collection of measures entitled **Optimized Reservoir Management (ORM)**, which can be applied in inundated areas to mitigate issues or eliminate risks primarily for the fish. These measures can be combined to target several challenges at a given site. When doing so, it often needs to be synchronized to achieve sustainable hydropower (and other use of damming in the case of multipurpose dams) operations. Measures as part of ORM will be marked throughout the Roadmap with an ORM suffix (e.g., *Storage level reduction (ORM)* in Section 4.3 and *Aeration technologies (ORM)* in Section 4.5.2, among others). Impounding a watercourse transforms lotic (flowing water) conditions into a lentic (still water) environment, as discussed in Section 3.2.2. Such conditions remain while the associated dam and structures are in place and not removed.

A by-product of this phenomenon is the risk posed by **habitat and biodiversity reduction**, as floodplain habitats are affected. To mitigate this, **artificially created (bypass) channels** in the nearby river sections with habitat characteristics similar to natural floodplains may be effective. However, it should be noted that this approach has had variable success and may be limited by land availability or other anthropogenic uses of floodplains.

Other impacts from terrestrial and floodplain impoundment have been covered in Section 3.3. Means that are available for mitigation of these potential impacts are mainly shown in Tables 4.7, 4.9, and 4.10 and include the following [4.42]:

Storage level reduction (ORM) in ecologically sensitive periods may be required to maintain reservoir level within a certain range and to limit its variation. The reduced water level at the inundated area increases the flowing water over habitats. It reduces the impacts of impoundments in general.

Manage shore/shallow habitats (ORM) by implementing simple measures, like shoreline maintenance and vegetation cover, to control erosion and plant overgrowth in the littoral zone. Re-naturalization of reservoir shores and artificial habitats are also suitable techniques.

Lateral connectivity is achieved with the periodic inundation of the floodplain or backwaters adjacent to a reservoir and enabling an exchange of water, sediment, nutrients, and organisms between the outer floodplain and the inner inundated regions. Maintenance of lateral connectivity is especially important in large rivers with broad floodplains, influencing species richness and compositions. **Enhanced lateral connectivity** can be maintained, created, or controlled as a fundamental ecosystem restoration component. Improving conditions include submersed check dams, connection channels, levee setbacks, notched dikes, culverts, and managed water level changes.

In-channel habitat improvement is a type of mitigation that aims to support healthy fish populations. Restoration measures may include [4.43]:

- Creating species-specific spawning habitats (e.g., seasonally flooded marshes and wetlands, stream channels, or riffle areas with the clean gravel-cobble substrate, adding gravel to shallow littoral areas, cobble-rubble in fast-flowing streams, among others).
- Stabilizing banks and reducing shoreline erosion.
- Clearing obstructions that impede water flow and fish movement.
- building and deploying underwater instream structures (e.g., half logs, brush shelters, log cribs, root wads, among others)

Creation or restoration of habitat in tributaries is also an option for mitigation (many fish use tributaries for spawning and feeding). Similar techniques can be used as presented for in-channel habitat improvements, but usually on a smaller scale, for tributaries along the inundated area.

Terrestrial impoundment creating significant **decomposition of inland vegetation** can pose another risk to fish. It may dramatically impact water quality and, consequently, fish populations over the longer term. During the construction phase, **vegetation reduction** is often recommended from the flooded area before inundation. This will reduce the amount of biomass that will eventually decompose. However, another school of thought suggests retaining all or part of this flooded vegetation to provide other forms of underwater habitat.

In larger reservoirs, further negative consequences may affect the local fish community.

Fish migration can be significantly impeded in a lentic environment with many side branches and tributaries where migratory fish depend on specific hydraulic or biochemical cues to navigate farther habitats. In some instances, it is possible to implement **collection systems (T&T)** to capture and carry threatened species upstream or downstream and past multi-reservoir systems. The selected measures can complement other fish passage facilities depending on the ecological targets and the population status of the affected species. These fish passage facilities should be tailor-made and operated specifically for the fish species of interest.

Another risk posed by reservoirs is the **invasion of exotic species**. Where the chance of occurrence is potentially high (i.e., where lower river sections are already infested), it is crucial to **exploit the swimming capabilities and the migratory strategy of native species to design and operate fish passage facilities** accordingly. Alternatively, **collection systems (T&T)** might be operated to deselect non-native species. The lack of fish passage facilities in severe invasions might be the best practical solution to protect and preserve the upstream populations. In cases of invasive species, decisions must be based on comprehensive ecological studies of the affected area.

4.4 Sediment Management

As noted in Section 3.2.3, two major and interrelated environmental challenges are associated with sediment accumulations in the reservoir. First, the sediment accumulations affect the habitat within the reservoir and deprive the reaches downstream of their natural sediment transport and accumulation conditions. The second challenge relates to releases of sediment accumulations from behind the dam and its impact downstream, leading to increased turbidity or causing habitat degradation due to e.g., embeddedness.

Sediment accumulation starts when the natural river runs into the inundated area**.** This process affects habitats and fish communities upstream and downstream of the barrier. To manage this process from the perspective of hydropower plants, many dams are equipped with sluices or low-level outlets designed to **flush** excess **sediments downstream** past the dam. However, such measures are primarily suitable for mobilizing sediment depositions near the sluices. While it is acknowledged that these sediments would travel downstream naturally under the free-flowing river regime, flushing typically produces a more intense discharge over a shorter interval of time and a **potential increase in turbidity** that can affect fish populations. In addition, flushing that takes place at a critical period in the life cycle of certain species can pose an unexpected and unnecessary risk to fish populations downstream, like embedding voids in the gravel habitats downstream used as shelter or spawning sites for fish.

Therefore, assessing any ecological implications for the applied sediment management practices is important to prevent any additional negative consequences of uncontrolled sediment management. For instance, sediment flushing activities must occur during non-critical periods for fish and, if possible, scheduled during high-flow conditions, such as floods, when re-mobilized sediments would be transported farther downstream. In addition, the levels of turbidity caused by sediment flushing should be monitored (see Section 6) during operation to ensure "safe" levels (in terms of tolerable opacity and suspended particles in water for fish) in river sections rich in habitats.

Additional approaches may also be used to manage and/or mitigate these issues [4.42][4.44].

Mobilizing flows may be viable for managing already accumulated sediments downstream of the dam. The aim is to carry the coarse and fine material farther downstream in the river as they may be aggregated at habitats. Like sediment flushing at the reservoir, mobilizing flows shall be ecologically optimized to reduce the negative impact on aquatic life.

Dredging is a conventional measure to remove sediment at concerned river sites (using various equipment). Except for sedimentation issues in large reservoirs, it can be applied on different scales, from shoreline regions or floating platforms and vessels. However, it should be noted that mechanical removal of sediments is often costly, has a high risk of damaging benthos and their organisms, and poses problems in finding appropriate deposition zones where the excavated sediment material can be stored in the long term. Therefore, it is often minimized in use.

Re-introduction of sediments from the inundated area downstream of the dam. Besides flushing through sluices and low-level outlets, sediments may be transported **passively** through special weir designs for floodplain impoundments and RoRs or through constructed bypass channels for larger reservoirs (terrestrial impoundments).

Active re-introductions, (also termed replenishment) may be an option for both storage and RoR systems when the dredged material from upstream is being returned to the river downstream of the dam (Figure 4.22). An alternative for active measures is implementing a fully automated floating platform that allows continuous sediment removal (like a hydraulic dredge). It consists of a suction unit at the upstream end equipped with a screw cutter to mobilize sediment. It is led through the suction line towards the floating platform. A rotary pump is located at the platform that operates the transfer line to transport sediment downstream. The amount of sediment to be reallocated from the reservoir to the river downstream relies on the speed of the rotary pump and the positioning of the suction unit [4.45].

It is imperative to address sediment imbalances due to damming, especially for RoR developments. Providing such measures is necessary to avoid **sediment starvation downstream of the river**. This can create significant damage and alterations to habitats. In case the re-introduction of sediments is not a feasible option to address sedimentation challenges downstream of the dam, other techniques shall be applied.

Introduction of sediments downstream of the dam by active or passive measures. In the former case, vessels filled with sediments dump their load in the river below the dam. In contrast, in the latter case, sediment deposits are placed near the shoreline. In both cases, the flow gradually erodes the deposits and transports them downstream. Therefore, it is important to determine the grain size distribution according to the local needs, including ecological interests, to prevent unfavourable deposits or clogging.

Figure 4.22 ***Process of sediment feeding on the River Rhine***
(Source: Marcell Szabo-Meszaros)

Restoring the lateral erosion process also aids sediment balance downstream of the dam. When there are no constraints, such as safety or land use, removing erosion control structures from the riverbanks will enhance local sediment supply as the river naturally erodes materials.

Under some conditions, sediment transport capacity exceeds the sediment supplies downstream of the dam, in which cases **bed armouring** may occur. It can also occur when frequent low-magnitude flows transport fine sediments while the coarser bed material compacts. The armoured riverbed's **mechanical breakup** can restore lost habitats, **combined with adequate flow releases** to support self-sustainability (i.e., to prevent additional compaction).

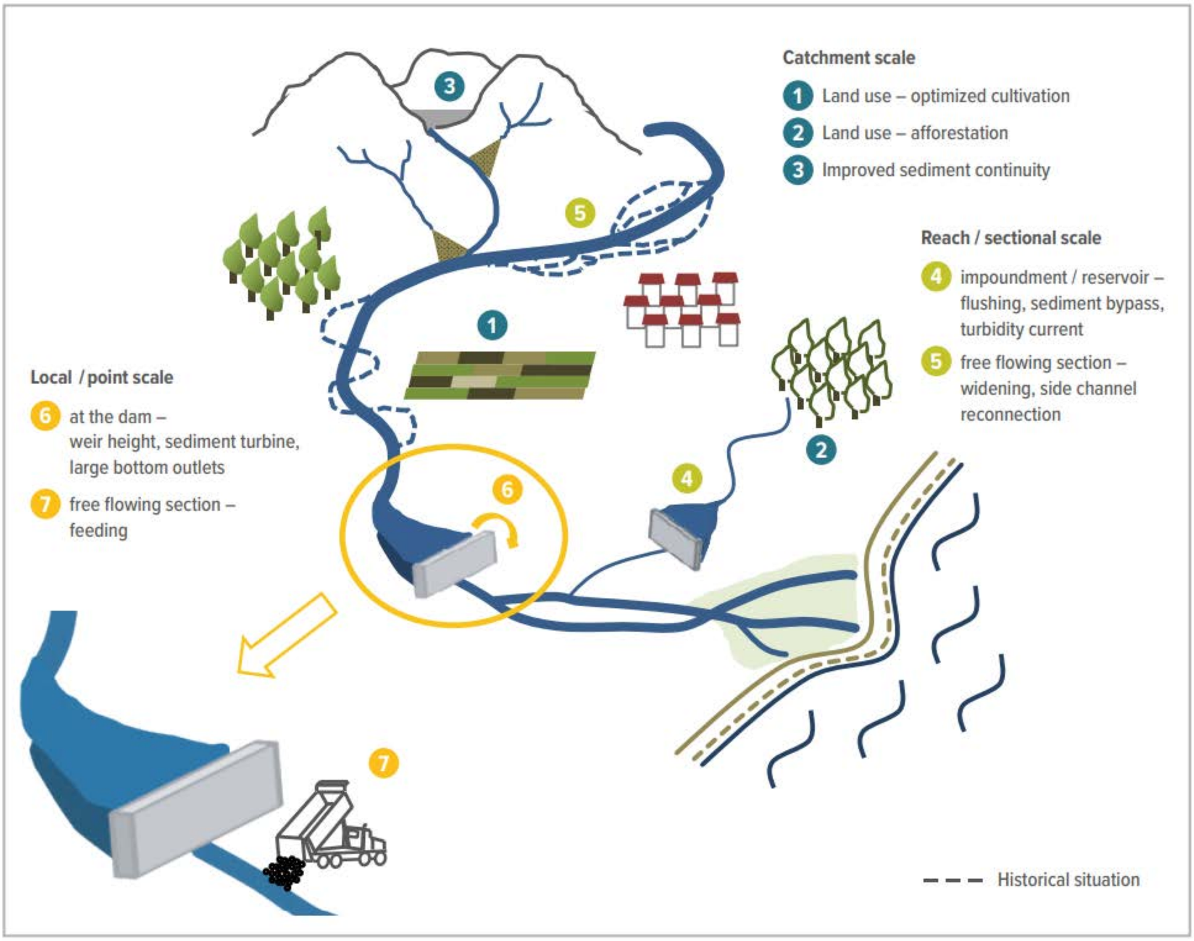


Figure 4.23 ***Overview of measures to manage sediment within a basin*** (Source: [4.46])

In some rivers and streams, where sedimentation levels are extreme, heavy erosion processes occur in a catchment comprising many erodible materials. This can also be more critical when combined with extreme precipitation and altered land use. Where the accumulation rate of sediments in the reservoir is high, it may be necessary to introduce **sediment management on a catchment scale**, including altered land use, increased forestation, especially close to the river, and the application of sediment retention structures in critical areas (Figure 4.23).

4.5 Water Temperature and Water Quality

Damming a river and creating inundated conditions create physicochemical changes in a regulated watercourse, some of which may have significant consequences for the freshwater ecology, needing efficient and effective mitigation. Changes to temperature, dissolved oxygen, and primary nutrient levels are generally addressed in the Roadmap; however, the list of impacts and sustainable options to address them is more complex than those introduced below.

4.5.1 Temperature and Stratification

Temperature change in the watercourse affects both the reservoir and the downstream sections. Recovery and management of temperature dynamics in streams and reservoirs should identify external drivers and local temperature modifiers across basins [4.47]. Models can support identifying areas to focus efforts and meet local- and basin-level temperature goals. Mitigation measures are depicted in Figure 4.24 and detailed below.

Downstream of a barrier, several measures can mitigate the thermal effect of damming in some rivers by **adding gravel bars** in the hyporheic zone along the riverbed. Due to the permeable structure beneath and along the streambed, groundwater and river water mix slowly. Significant thermal exchange occurs if the temperature from the two sources differs. Ecological benefits from such measures could include the porous bars being also used as a habitat for fish; for instance, they may act as thermal refugia for fish [4.48][4.49][4.50].

On the other hand, such measures may be challenging to apply efficiently on large rivers. Another solution for mid-size and smaller rivers is the **removal of erosion control structures** (to restore lateral erosion processes). This approach can be adopted where the floodplain area is wide enough to enable the river to meander and does not risk any successful flood protection nor interfere with other purposes (e.g., land use). The natural development of the river channel through meandering and widened sections can also facilitate thermal balance in shorter ranges below the dam [4.50].

In some cases, **restoring riparian trees or reservoir trees along the riverbank or reservoir shoreline** will help reduce temperatures by providing shade [4.51]. Restoration of upland habitat, trees, and vegetation can reduce runoff and erosion while regulating water temperature. However, in catchments with large reservoirs having large runoff volumes, this solution will be less effective.

The temperature imbalance of smaller reservoirs in ecologically critical periods can also be mitigated effectively when **inflow** from the upper reservoir(s) is **increased (ORM)**. It is a viable option in multi-reservoir systems, however challenging if a different owner operates the upper reservoir(s).

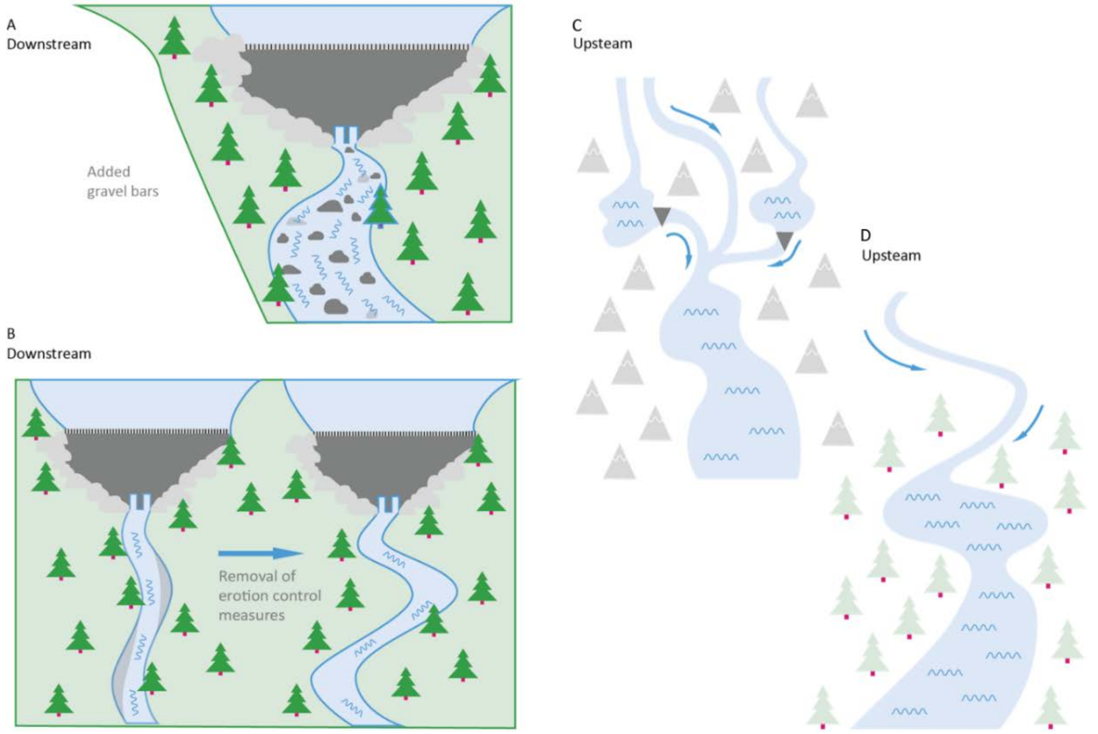


Figure 4.24 ***Illustration of measures to balance thermal differences downstream by adding gravel bars (A), by removal of erosion control structures (B), and through measures upstream like increased inflow from upstream reservoirs (C) or by restoring shoreline trees (D)***
(Source: SINTEF Energy Research, Norway)

Releasing water from the barrier at different depths can also affect the health and survival of fish and other aquatic organisms downstream. Structural measures can be adopted from smaller to more extensive systems to control the water temperate below the dam. **Intakes with flexible sill level or multiple level configurations** (for new developments) may address temperature issues downstream, based on the mode of operation. For older dams, other technologies, such as sliding gates at intake structures, can assist with the release of water from different depths. In either case, the system requires temperature monitoring at different reservoir depths and downstream of the dam.

There are reservoirs where the local conditions can lead to thermal stratification. While the fish attempt to migrate through reservoirs, they may experience **sudden changes in temperature** or **reduced habitats in the reservoir hypolimnion**. In the former case, the conditions may hinder fish migration through the reservoir, where collection systems, such as **Trap and Transport**, could enhance connectivity in migratory seasons. The latter condition is an example of detrimental changes in water quality affecting habitats, which is addressed in the next section.

In many sites, especially those in the tropics, the behaviour and depth of the thermocline are poorly understood, making it challenging to plan for or implement structural thermal mitigation measures (e.g., selective withdrawal through intakes) or to provide thermal mitigation through instream flows or spillway flows. This underlines the need for monitoring activities to fill this gap and enable the selection and implementation of effective mitigation strategies.

4.5.2 NUTRIENT LOADS AND FURTHER CHEMICAL CHANGES

Chemical processes, which occur naturally in an undisturbed watercourse, may change upon hydropower development on that stream. This will have consequences on aquatic life as well, perhaps negatively. Commonly such changes are driven by temperature alterations. Building upon solutions that assist with temperature management, various methods have been introduced that improve water quality in reservoirs or manage it downstream. Here the focus is on preventing or mitigating toxic processes and improving dissolved oxygen in watercourses. To increase probabilities to understand whether these measures will occur, it is important to **identify the main cause or causes of the unfavourable water quality**.

Like sediment accumulation, reservoirs can also capture nutrients, leading to eutrophic conditions, causing algal blooms and **oxygen depletion** in the inundated area. It is a risk on sites where phosphorous and nitrogen concentrations have increased due to anthropogenic sources, such as agricultural activities in the catchment or the release of untreated wastewater into the watercourse. The best practice in these cases is **catchment-scale management of nutrients**. This includes comprehensive long-term actions from regulating land-use activities, developing sewage systems and wastewater treatment in the watershed, reducing runoff loads by forestation, and increasing vegetation islands. Short-term action targets the reservoir directly and includes **removing the top silted layer (ORM)** along the waterbed. Biological intervention is one possible solution in areas where nutrient levels are naturally high. By **creating a smaller reservoir in a nearby upper region** to the inundated area, natural processes can help to decompose organic compounds and filter the nutrient-rich inflow before it runs further into the more extensive reservoir.

Another form of biological intervention in reservoirs is **sustaining or improving conditions for native filter-feeding organisms (ORM)** with critical ecological services. These can improve water quality by filtration of algae, suspended particles, and micronutrients from the water column.

Example: the duck mussel (*Anodonta anatina*) is a freshwater mussel found in many European lakes and slow flowing rivers. It filters plankton and suspended particles from the water, and even lead to decrease of fish pathogens in the water. [4.52].

During the inundation phase, **algal communities** also change, which may **support the growth of aquatic plants in the reservoir**, such as macrophytes. The process also leads to oxygen depletion. When the main cause of low O_2 levels is the thriving of **macrophytes**, their **mechanical reduction (ORM)** helps to restore oxygen levels to normal levels. A variety of **aeration technologies (ORM)** have been developed to deliver oxygen immediately at the reservoir's surface (e.g., turbine, blower, oxygen injector). When flooded vegetation decomposes, many can already be used from the early inundation phase. In multi-reservoir systems, water releases from upper reservoirs can be operated to yield **increased inflows (ORM)** to the lower ones and thus restore acceptable oxygen levels. However, when different hydropower companies own reservoirs in a cascade system, it may be challenging to coordinate such activity. In saturated reservoirs, **anaerobic conditions may limit the use of habitats in the hypolimnion**. For such cases, **hypolimnetic aeration (ORM)** technology can be used to exchange water between the deeper region and the oxygen-rich epilimnion (Figure 4.25) [4.53]. At sites where released water to lower sections is frequently oxygen-deficient, hydropower plants with **self-aerating turbines** (Section 4.2.5) can be used to balance oxygen levels in the downstream section; however, supersaturated states must be avoided.

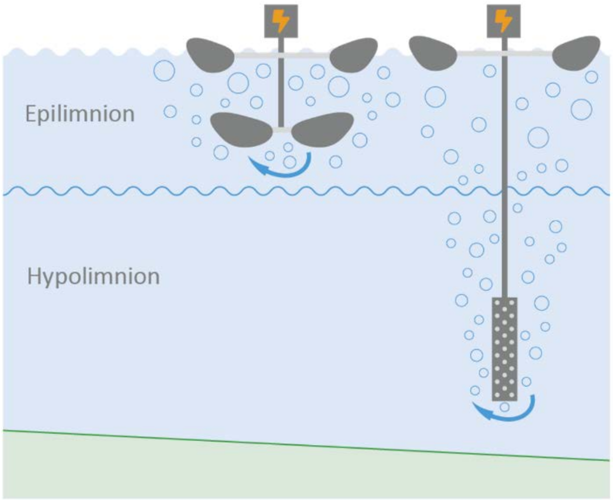


Figure 4.25 ***Illustration of aerator turbine (left) and hypolimnetic aeration (right)***
(Source: SINTEF Energy Research, Norway)

Water quality affects GHG emissions from reservoirs. Increasing the trophic state (one aspect of water quality that may affect some native fish species; it covers nutrients, the degree of biological production, and other biotic and abiotic elements) will increase the risk of methane production and **GHG emissions**. **Reducing vegetation** is an effective measure to reduce the risk of GHG release from the decomposition of flooded materials, as discussed in Section 4.3. After construction and during the operation of reservoirs, low water levels will increase the risk of methane bubbling from shallow areas. Therefore, **cautious operation of reservoirs (ORM)** to avoid exposing large areas of shallow depth (normally less than 10 m) will decrease the risk of GHG emissions. Making sure that the **intake level is above the oxycline** (reservoir layer, where oxygen concentration decreases rapidly with the increasing depth) would mostly eliminate the **risk of GHG degassing downstream**. Dissolved CO_2 and methane, carbon, and nutrient loading from unrelated anthropogenic sources, such as agriculture, forestry, industry, sewage, and households, may strongly impact GHG emissions. These sources are not related to hydropower and should not be considered when evaluating the carbon footprint of reservoirs and hydropower. Therefore, even though it is beyond the scope of the Roadmap to reduce the impact of global warming, it is a good strategy to minimize such dissolved gas, carbon, and nutrient loading to reservoirs.

4.5.3 SUPERSATURATION

Similarly to oxygen deficiency, a surplus of total dissolved gases is problematic to aquatic life. **Supersaturation** is generally limited to downstream zones. Flow becomes oversaturated by spilled flows from low- to high-head dams or unfavourable operating conditions at high-head hydropower systems. Systematic monitoring, i.e., frequent and representative sampling both spatially and temporally, should be undertaken to identify potential sources and periods to enable supersaturation impacts to be addressed effectively.

Where spilled flows cause problems to fish, **flow deflectors** or other similar structural solutions can be installed between the upstream end of the spillway and the water surface downstream. This can reduce the plunging effect by reducing the energy of the spilled water and enhancing outgassing efficiency [4.54]. Note that if a fish ladder is located near or at the foot of the dam, its entrance must be located to avoid highly aerated water flows.

Systems with air admission/injection can lead to high TDG levels in released water at the tailrace section. **Operational measures** (i.e., stop or limit air admission) can potentially limit the problem to ecologically tolerable levels in critical periods.

At high-head hydropower projects, the solution would be different. Based on experience from Norwegian research, the level of total dissolved gases can increase dramatically during floods when flow with entrained air is diverted through under-dimensioned creek intakes (i.e., high flow velocities at the intake and in the conduits and penstock) [4.54][4.55].

Of the common turbine types for high-head hydropower plants, Francis turbines pose a higher risk. In contrast, Pelton turbines are less commonly reported as having elevated saturation levels downstream. Flows discharged through Pelton turbines are more exposed to outgassing. Therefore, a **modified power station design and the operating regime** must cope with any challenges on high TDG levels. During the design phase for new hydropower, it is highly recommended to avoid steep shafts to minimize the oversaturation periods. Alternatively, **creek intakes can be retrofitted** with, for example, so-called **vacuum gates** [4.55], which prevent air entrainment into the tunnel system as long as a vacuumed state is maintained. Another alternative is **air detrainment devices** in small dome structures installed above the highest part of the tunnel to trap air bubbles and evacuate them through boreholes connected to the atmosphere [4.56]. Operating measures could include avoiding air injection systems or unfavourable operating scenarios, such as deficient lake levels at the central intake, which set the pressure line in the tunnel system to a lower level. Air entrainment may be problematic when combined with high flows through creek intakes with high operating loads. Measures such as **maintaining clean trash-racks** and **controlling the discharge at creek intakes** may also contribute to preserving acceptable oxygen levels in the power system. Other complementary measures, such as constructional or morphological types may be applied downstream of the HPP, either at the tailrace channel or within the recipient watercourse, respectively. Such measures are effective in reducing hydropeaking in the first place, and they may also be viewed as supplementary methods for supersaturation. Their main types and application are discussed in the recommendation for the design of hydropeaking mitigation in Section 4.6.3.

4.6 Regulated Flow and Water Abstraction

Altered flow distribution affects the environment on several spatial and temporal scales. Section 3.2.5 presents them as either limited to river sections and sub-basins or reaching inter-basin levels via different operational strategies.

Inter-basin transfer

Example: A recent study assessed the process of inter-basin transfers and uncovered the following high-risk traits; smaller body size, migratory behaviour, high local abundance in donor (intake) habitats, high larval drift occurrence, generalist, wide environmental tolerance, pelagic habitat association, and high fecundity [4.57]. The use and assessment of species traits, or characteristics, are helpful to studies of fish communities and phylogenetic groups, to both provide approaches for understanding the differences found between groups and to provide explanations for observed variation. For example, traits such as smaller body size may be related to weak swimming abilities and a greater tendency to be entrained. Or traits such as high local abundance or even a preference of habitats typical of intakes may also explain higher likelihood of entrainment since more individuals are in proximity to intakes.

Water allocation from an adjacent basin may **introduce new species**. Such findings, as presented in the right panel, can inform plans for new inter-basin transfers and **deployments of fish exclusion technologies** (e.g., physical barriers, sensory deterrents, turbulence, velocity-based deterrents, bar-racks, screens, among others, as presented in Section 4.2.5) to avoid or reduce introductions. An additional risk related to such actions is that water blended from two different catchments has an unknown **impact on fish natal homing**. Until more information is available, hydropower systems with inter-basin transfers pose risks to the affected freshwater ecosystems, especially where long-distant migratory species are present. Therefore, **monitoring activities are recommended to assess the impact**, especially on long-distant migratory species, and, if necessary, **limit abstraction from the donor basin** in ecologically sensitive periods. The same measure can also be applied when uneven flow distribution causes environmental problems in the donor basins due to the high or frequent water reductions. If in some cases, such measures are not feasible for whatever reason, water level variations can be limited to one or more parts of the reservoir by **creating separations** or **embayments (ORM)** where water levels are maintained even when water transfer continues [4.42].

Sub-basin Regulation

There are significant challenges associated with flow regulation. These include **uneven temporal and spatial flow distribution** within and between river basins or limited **organic and inorganic materials** between upstream and downstream reaches. Several issues or risks are site-specific and limited to sections along the regulated stream. At hydropower plants with extensive shore zones, **frequent reservoir drawdown** may lead to **desiccated vegetation or extensive flat shore areas becoming unsuitable for sustaining productive aquatic habitats.** Another risk associated with ecologically insensitive water reservoir level management is that **fish may become disconnected from tributaries** and their habitats. Bypass channels are also a common source of ecological concern due to their reduced flow; **perennial segments can dry out** since there will be **limited lateral connectivity with branches and floodplains**. Other issues relate to the hydropeaking operation and its effect downstream. It leads to elevated hydraulic shear stresses across the riverbed, which alters habitat characteristics downstream. Hydropeaking may yield stranded habitats and fish, including dewatered spawning areas and **increased drifts of prey and juveniles.** In addition, ramping flows may **disrupt attraction flow towards upstream passage facilities for fish.** However, the latter situation can be sufficiently addressed in the design phase or during the performance evaluation of existing fishways, as presented in Section 4.2.3.

In conclusion, any disturbance to natural **flow variability can disrupt habitat use and spawning patterns and limit the recruitment success** (transition from small to larger size and greater age of juveniles) **of fish populations** at selected river reaches or on entire watercourses. Therefore, it is essential to determine an adequate operational strategy for hydropower systems that address the abovementioned issues and risks and provides ecological services (e.g., for recreational purposes, fishing, and nutrient cycling, among others) beyond social, business, and other functions.

Licensing practices in many countries already require consideration of environmental concerns when determining flow management plans for new or re-licensed hydropower developments. For water level management in reservoirs, environmental requirements often compete with other restrictions based on the purpose of the reservoir. Common measures to counter water elevation changes in the reservoir are discussed in Section 4.6.1. Based on country-specific legislation, the **management of downstream flow,** including the bypass section, targets ecological needs through common approaches, such as minimum flow requirements, instream flow requirements, or environmental flow. The concepts and the main differences between them are discussed in Sections 4.6.2 and 4.6.3 for downstream flow regulation through selected methods from different countries.

4.6.1 IMPACTS OF WATER LEVEL MANAGEMENT IN RESERVOIRS

Flow regulations in reservoirs usually do not have as strict limitations as flow releases downstream. Optimized Reservoir Management (ORM) consists of various techniques (including operational and structural measures) that can support maintaining a suitable environment for the aquatic species living, using, or just passing reservoirs.

The highest and lowest operational water levels in the reservoir are usually part of the licensing requirements, which may prioritize services provided by the reservoir to manage environmental concerns. In some cases, the licensed water levels in the reservoir are also linked to certain periods over the year. Suppose the water level is normally maintained stable. In that case, there is a low probability of severe negative environmental consequences in the reservoir. Under other conditions, there is a risk of habitat and biodiversity reductions in the shoreline zone. To mitigate the effect of water level variations, the following measures may be considered solely or in combination:

- **Create embayment (ORM)** in one or several parts.
- **Reduce excessive abstraction (ORM)** to keep water level stable for an ecologically sensitive period (both measures introduced formerly in Section 4.6).
- **Increase inflows (ORM)** from any upper reservoir in multi-reservoir systems (see Section 4.5.2) [4.42].

Shoreline habitat management (ORM) is another suitable option to re-naturalize or sustain living spaces for aquatic organisms in shallow regions (see Section 4.3). Similar measures can also increase the available habitats in reservoirs even with frequent water level changes. **Artificial floating islands (ORM)** follow level variations in the reservoir while providing valuable habitats for fish and other aquatic organisms for rearing, spawning, or sheltering. They may consist of bundles of large woody elements or constructed island/reef structures with an empty basket suspended underneath. Different basket mesh sizes can be selected for different life stages/species [4.42].

At many sites, fish may migrate between the reservoir, its tributaries, and small creeks to reach different habitats in the upper, free-flowing reaches. When the reservoir is operated with frequent or significant water level drawdowns, fish may face difficulties moving freely between their various habitats. Therefore, in these sections, **maintaining connectivity to tributaries (ORM)**, as water levels vary in the reservoir, is important. Fishways (see Section 4.2.3) can be implemented according to local needs.

4.6.2 FLOW REQUIREMENTS IN BYPASSED RIVERS: CONDITIONS FOR HEALTHY FISH POPULATIONS

The regulation of flow releases downstream of hydropower plants aims to meet fish species' and populations' ecological requirements and mimic other natural processes on sites affected by hydropower. The former case is discussed in the present section, while the latter is addressed in Section 4.6.3.

There is no simple rule for determining the necessary flows to support fish and ecosystem functions at a hydropower site. However, numerous resources support decision-making and select appropriate methods considering site complexity, data availability, and risk. Hydropower owners and operators know that flow requirements for fish can affect the amount and timing of power generation. It can range from a few percent of revenue loss in many cases. For example, the requirements where environmental flow requirements ranged from 20-30% of seasonal river discharge threatened the viability of a project in India. However, these conditions helped maintain the river ecosystem and habitat quality that sustained the fish populations, providing reasonable measures for long-term sustainable hydropower operations [4.58].

Hydropower flow requirements are diverse and often specified in terms of a license or during permitting. In the USA, requirements include minimum or maximum flows, ramp rates, and other conditions. A study of 50 privately-owned hydropower projects, licensed by the US Federal Energy Regulatory Commission (FERC) categorized 1,449 unique flow requirements, including some targeted for fish spawning, recreation, and general river condition maintenance [4.59].

There are two main approaches to set conditions for flow releases for the fish: **minimum flow** and **instream flow requirement**. The latter is designed to maintain fish habitat, focusing on low flows in the wetted channel [4.60]. The former describes a minimum, often constant, flow maintained for a specified period (e.g., dry season, the entire year) to support ecosystem functions and fish. Hydropower plants with storage can meet minimum flow requirements by partitioning water to the bypass reach and/or releasing stored water at the powerhouse. Although minimum flow does not account for the flow variability within and between seasons or years, which is essential for healthy rivers [4.60], it is a common requirement in the USA. In contrast, instream flow requirements are site- and species-specific.

Planning flows for different fish species and communities should consider fish's annual life histories, dispersal strategies, habitat characteristics, and the natural variation of the river over time. Most instream flow assessments start with reviews of technical and scientific information to determine fish habitat preferences. The Flow Duration Curve of the basin, i.e., the historical flow at the location in order from maximum to minimum (cumulative frequency), is used to assess the relationship between the magnitude and frequency of streamflow on different timescales (e.g., daily, weekly, monthly) [4.61]. The Flow Duration Curve can also be used to assess the potential impacts of providing residual flows on the flow capacities of the project for energy generation.

There are many available methods to evaluate instream flows with different costs, specificity, and data needs. In Washington State, U.S.A., four methods are used to determine instream flow requirements: Instream Flow Incremental Methodology (IFIM), Toe-width, Wetted Width, and Hatfield and Bruce method [4.62]. The widely accepted IFIM uses computer-based models (e.g., the Physical HABitat SIMulation (PHABSIM)) to calculate fish habitat gained or lost as streamflow increases or decreases. Other methods range from simple calculations and measurements to determine spawning, rearing, or precautionary low flows, to advanced simulations building on IFIM to provide detailed habitat flow requirements for sensitive fish species. The guideline is available for IFIM studies, habitat assessments, and methods to account for ramping rates and habitat maintenance flows [4.63].

In conclusion, minimum flow requirements are developed to ensure the absolute lowest quantity of water is released constantly while developing and setting instream flow requirements that consider different fish species and their habitat requirements, thereby providing a more tailored, fish-friendly approach. Various methods determine the different flow requirements for healthy fish populations. However, they usually do not account for the affected riverine ecosystem's overall needs because they consider some episodic or periodic processes found in natural dynamic systems contrary to the concept of environmental flows, presented in the next section (Figure 4.26).

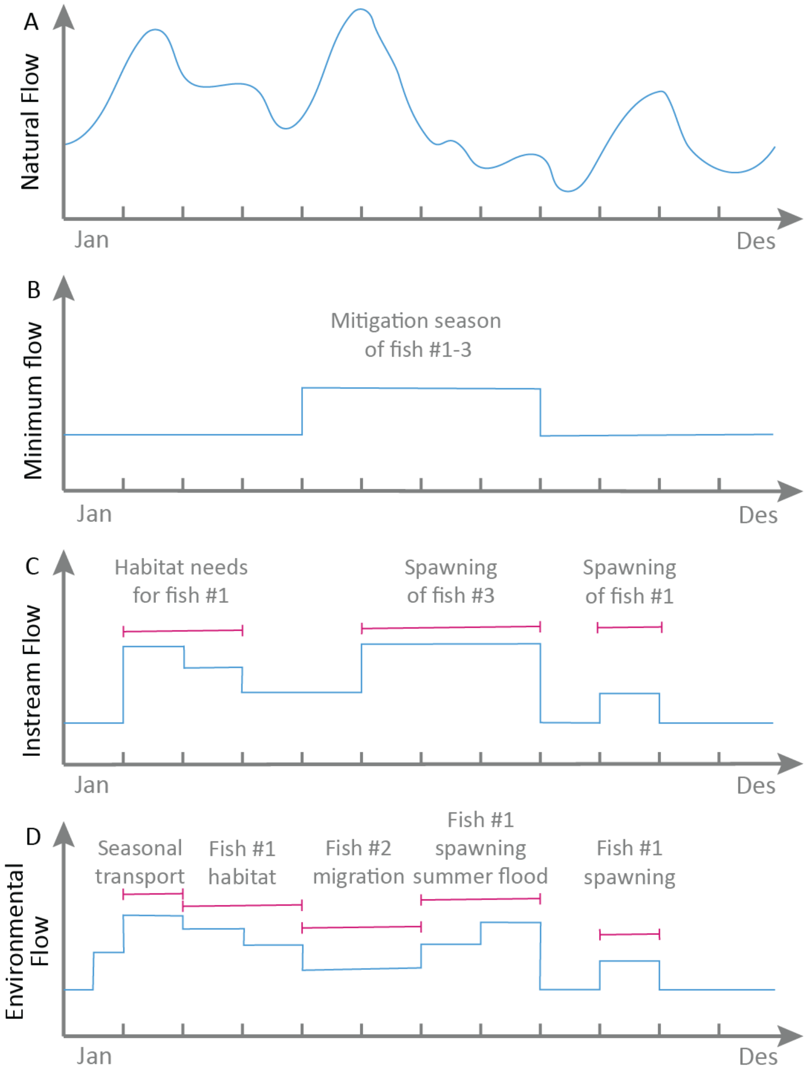


Figure 4.26 ***Illustration of minimum flow (A) vs. instream flow (B) vs environmental flow requirement (C)*** (Source: SINTEF Energy Research, Norway)

4.6.3 FLOW REQUIREMENTS DOWNSTREAM OF THE HYDROPOWER PLANT

Environmental Flows for Healthy Rivers

Environmental flows provide a holistic approach to ecosystem management and help mitigate some of the negative impacts of flow diversions by utilizing flows to protect ecosystem services. The 2007 Brisbane Declaration defines environmental flows (also referred to as e-flows) as "*the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems*." As environmental flow is considered the best practice for flow releases in modern hydropower development, this section provides further information on determining and implementing it for specific projects. The presented concept can also be applied to control hydropower flow releases through the tailrace, particularly at plants with flexible operation.

There is broad scientific support for moving beyond setting instream flows as minimum flows for fish and incorporating variability into regulated flow management to mimic nature and deliver representative environmental flows. In general, dam and HPP operations affecting habitats can potentially be reduced by appropriately managing water releases (e.g., timing, quantity, frequency, rate of change, and magnitude) such that they are delivered to reflect natural processes better and maintain or create downstream habitat, or to minimize harmful impacts on impounded littoral habitats. Nevertheless, a key challenge for regulated rivers is the uncertainty between flow releases and ecological responses at different scales [4.64]. Globally, there are over 207 different methods for determining environmental flow recommendations [4.58][4.65][4.66], and the selection of suitable methods out of this diverse menu may be a barrier to implementation.

The recommended best practice is to tailor technical and data requirements to the specific context of the dam to determine the timescales of streamflow variability necessary to meet ecosystem needs and suit flows according to sensitive species thresholds.

Desktop hydrological methods that are not site-specific and assume ecological characteristics are typically used as a preliminary step. For example, the Indicators of Hydrologic Alteration software enables comparisons of reconstructed natural conditions to be measured regulated flow regimes and utilizes 33 parameters in five dimensions (flow magnitude, timing, duration, frequency, and change rate) in evaluations [4.67]. Using the Indicators of Hydrologic Alteration technique with ecological models provides a means of developing and testing ecological flow questions regarding fish protection and restoration goals and evaluating outcomes with an effective research and monitoring plans [4.68]. Another method, the Tennant method, correlates the percentage of mean annual flow at different timescales to the ecological environment to calculate the water needed to maintain certain ecological functions. In practice, the Tennant method shows that 10% of the mean annual flow is needed for the survival of most aquatic organisms, 30% is recommended as suitable, and 60% is the best runoff for most aquatic organisms [4.69]. Thus, some areas have used 10% of the mean annual flow as a generalized minimum flow threshold. For example, this 10% mean annual flow is a minimum requirement in China's environmental impact assessment process. **However, a single threshold does not support sustainability goals with complex water uses and ecosystem needs** [4.64].

Hydraulic, habitat, and holistic methods can also inform environmental flow recommendations. Still, the amount of data required, cost, and expertise for analysis increase as more aspects are incorporated [4.66]. As downstream effects of dams and new insights into micro-habitats are better understood, there is a transition from coarser hydrological methods to incorporating holistic methods and adaptive management [4.70].

A group of researchers presented a three-tiered approach to assessing and implementing environmental flows and providing case study examples [4.71][4.72]. The three tiers frame techniques for implementing environmental flows, following the availability of resources (Tier 1: desktop analysis; Tier 2: develop flow recommendations by an interdisciplinary set of experts; Tier 3: test hypotheses developed by the experts). Briefly, there are several ways in which environmental flows can be implemented:

- Including managing water withdrawals.
- Changing dam and HPP operations (e.g., operational restrictions).
- Altering the design or location of infrastructure.

Managing water withdrawals is especially important in water systems with multiple purposes (e.g., storing water for hydropower and water for irrigation infrastructure). There is a risk of excessive withdrawal disrupting freshwater ecosystems. This is particularly true for arid or semi-arid environments. Increased demand for water resources results in lower prioritized environmental flows. Water withdrawals may be optimized based on flow timing, duration, or volume. They may also be managed by targeting water volumes from different reservoir levels.

Dam operations may vary significantly on intra- and inter-annual scales based on the timing and magnitude of river flows, the ability of which is set through storage in the reservoir. Power production models can explore operational strategies that consider this variability. Researchers developed an assessment framework to evaluate how dam operations impact river flows and explore the potential benefits of modifying dam operations to emulate a more natural flow regime [4.73]. When exploring operational strategies, it's essential to consider that the dam's economic purposes and potential impacts on water rights and power purchase agreements may limit the implementation of environmental flows [4.72].

Dam infrastructure, particularly outflows, largely dictates how water is managed and released, and releasing variable water volumes is a recognized challenge [4.73]. Aside from changing the design or location of infrastructure to manage releases, policies may also be developed to maintain free-flowing conditions on the river [4.72]. Due to the rapid development of water infrastructure and environmental flow protections that have only been implemented in a select few systems, a regional approach to developing standards for environmental flows would help implement a larger geographic scope. The Ecological Limits of Hydrologic Alteration framework (ELOHA) offers a framework for developing recommendations across a region for environmental flows [4.74] and can be applied to determine a precautionary flow recommendation as to the first step in a desktop assessment [4.71].

When environmental flows are being determined, they should consider the river's natural flow regime and intra- and inter-annual flow variability rather than solely specifying a minimum low flow threshold. Aside from flow requirements, environmental flows should likewise consider the movements of aquatic species, other riparian vegetation needs, and sediment transport [4.60].

Various software and models can support assessments to inform environmental flow recommendations. The World Bank Group also provides a decision support tree for selecting environmental flow methods based on site characteristics and complexity. It presents a matrix of 14 permutations of dam location, design, and operation that range from low-impact designs to medium and large storage dams. The reader is guided to check [4.60] for more in-depth information.

Based on the recommendations developed by the World Bank Group [4.60], Table 4.4 (below) describes the steps, key considerations, challenges, and resources that may help determine environmental flows.

Table 4.4-A ***Summary of some typical steps, considerations, and challenges to assist in determining environmental flows***

STEPS IN SETTING E-FLOWS	KEY CONSIDERATIONS	CHALLENGES	RESOURCES
STEP 1. Gather information to provide context to e-flows	- **river** functions and indicators - **ecosystem** values and services - **critical** and natural habitats - **historical** hydrograph data - **historical** species monitoring data and information - **policies** and laws - **global** change predictions - l**ocal**, regional, or national species, water, and habitat management plans and goals - **cultural** values	- **historical** information and data may be lacking - **ecosystem** values may be variable or conflicting between stakeholders - **river** functions may be impacted by other areas or input - **global** change predictions are based on models with varying levels of uncertainty - **available** information and data may not be easily assessable or formatted for comparisons	- **biological** inventories held by governments, organizations, institutions, and industry - **local** knowledge - **traditional** ecological knowledge - **economic** data and information on the monetary value of resources
STEP 2. Determine potential downstream impacts	- a **type** of hydropower plant - **level** and timing of the impact - **listed** species and species of concern - **habitats** and ecosystems - **social** aspects - **safety**	- i**nformation** and data on species occurrence and abundance may be lacking - **habitats** may not be identified or delineated - **cumulative** impacts may be difficult to quantify or estimate - **basin-level** assessments add complexity	- **unmitigated** impacts associated with permutations of hydropower design and location [4.60]

Table 4.4-B ***Summary of some typical steps, considerations, and challenges to assist in determining environmental flows***

STEPS IN SETTING E-FLOWS	KEY CONSIDERATIONS	CHALLENGES	RESOURCES
STEP 3. Clarify requirements	- l**evel** of detail or resolution (low, medium, or high) needed for decision-making - **preference** for prescriptive or interactive output(s) - **data** requirements - **time** and cost constraints - **consideration** of climate change effects		-**data** requirements for assessment of environmental flows [4.60] -**costs** for environmental flow assessments with different resolutions [4.60] -**additional** guidelines[4.75] and [4.77]
STEP 4. Select and apply an appropriate e-flows method for assessment	- **goals** for the river - **complexity** of the site - **impact level** of design - **impact level** of operations - **determining** the level of ecosystem services to maintain -the **importanc**e of different parts of the flow regime/ hydrograph to the maintenance of ecosystem services - the **ability** to incorporate episodic or periodic events into management - **hydropeaking** operations - **downstream** habitats and ecosystems - **social** dependence - **water** rights - **jurisdictions** and boundaries - the **spatial** context in the basin (e.g., other hydro plants, location in cascade)	- l**ack** of validation of various models - **differing** opinions on goals, impacts, and values	- **decision** tree for required resolution for environmental flows [4.60]:

Table 4.4-C ***Summary of some typical steps, considerations, and challenges to assist in determining environmental flows***

STEPS IN SETTING E-FLOWS	KEY CONSIDERATIONS	CHALLENGES	RESOURCES
STEP 5. Comprehensive stakeholder engagement for e-flows decision-making	- **clarify** potential impacts and benefits (environmental, social, economic) - **conduct** studies as needed - **determine** potential mitigation options - identify trade-offs	- choosing a specific methodology - **identifying** stakeholders and ensuring representation - **negotiations** on e-flows allocation	- **commonly** used methods for environmental flow assessment [4.60]
STEP 6. Implementation	- **determine** monitoring targets and metrics - **Management** Plan - **reporting** requirements **- independent** auditing		- **examples** for environmental flow management plans [4.60]
STEP 7. Adaptive Management	- **evaluate** outcomes - **modify** methods to meet targets - **communication** across operators, organizations conducting monitoring, and relevant agencies		- **adaptive** management system for environmental flow management plan [4.60]

Recommendation for Design of Hydropeaking Mitigation

Hydropeaking can affect the aquatic ecosystems in the recipient river section. Based on knowledge of frequent flow ramping, fish mitigation measures have evolved to ensure sustainable fish populations in hydropeaked river sites [4.78][4.79]. Here we structured the relevant solutions as operational, structural, and morphological measures.

Operational measures require hydropower operators to control flow releases at the hydropower plant (and at the dam structure) to sustain fish communities downstream (similar concept as **Ecologically improved operations** presented in Section 4.2.5 for downstream migratory fish). Figure 4.27 presents the main operational measures for hydropeaking focusing on fish. They include measures like **gradual (smoothened) operation with thresholds for up- and down-ramping** (i.e., water level change in cm/hour) so fish have more time to respond to the changing flow rates [4.80], **reduction of discharge extremities** (flow ramping ratio) or **peaking frequency**. The **increase of base flow** (the minimum flow released through turbines during flexible operation) shall reflect the need of fish species in their relevant life stages at the downstream sections [4.81]. It is recommended as a best practice that the base flow release is determined similarly as presented for the **environmental flows**. **Adaptive hydropeaking** introduces seasonal/daily restrictions to flow ramping during critical seasons for the different fish species, like during fry emerging periods [4.81].

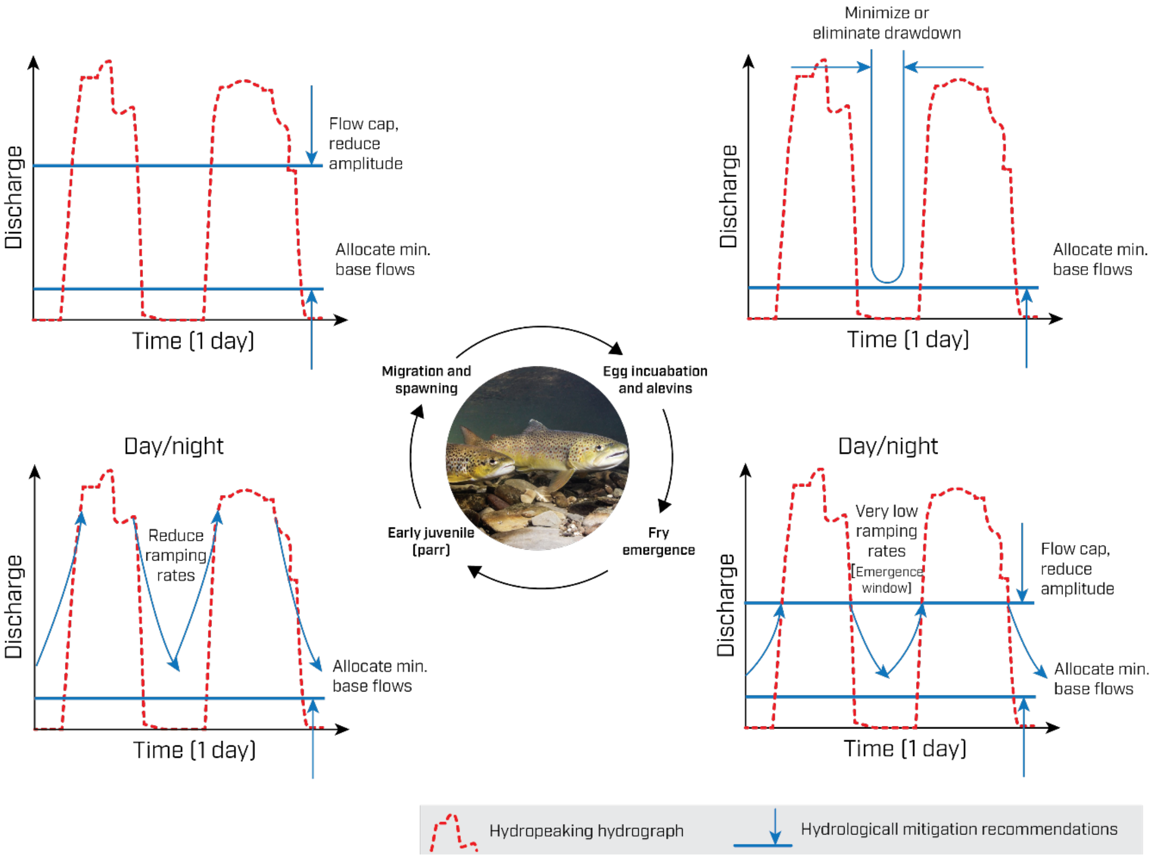


Figure 4.27 ***Life stage specific hydropeaking restrictions*** (modified from: [4.81])

Constructional measures are limited to the civil structures of the hydropower facilities. The **Retention basin** is located near the tailrace channels [4.82]. It works as a buffer between the hydropower outlet and the recipient river section to dampen the effect of hydropeaking before it is released further downstream (Figure 4.29). Retention basins can be implemented as instream or external (riparian) balance reservoirs or underground caverns with or without air cushions [4.83]. An alternative to retention basins is **diverting high discharge flows into a man-made channel** parallel to the recipient river section. Another constructional measure is to **relocate the hydropower tailrace** into a natural retention volume or larger water body (i.e., reservoir, ponded river, or sea if HPP is located near the coastline)[4.84].

In addition to planned hydropeaking, accidental turbine flow depletion may occur irregularly, due to technical failures or extreme weather events, for example. To avoid such abrupt dewatering events downstream of HPPs, automatically operated **by-pass valves** (BPVs) are advised to install (Figure 4.28). With such a measure in place, the aim is to release a certain amount of base-flow into the tailrace tunnel during sudden turbine shutdowns, which reduces the risk for fish stranding downstream of the HPP [4.85]. BPVs have become part of best practices in

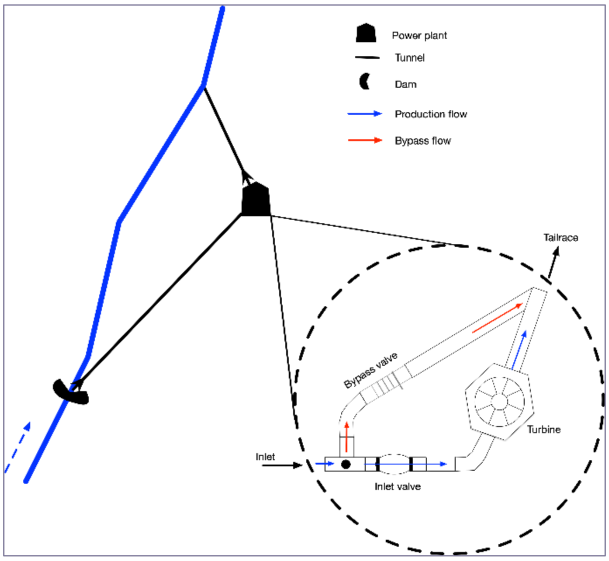


Figure 4.28 ***By-pass valve allows constant flow release downstream in case of emergency*** (modified from: [4.85])

Norway, California (US) and the EU. Still, accidental HP turbine fallout occurs on a rare basis but may increase in the future due to more extreme and severe weather events from climate change.

Example: In the River Yuba, (California, US), two large BPVS was installed to mitigate unscheduled shutdowns of the Narrows 2 HPP, (operated between 25 to 96m^3/s flow rate) below the Englebright Dam. The first BPV was set with a partial flow rate of 18m^3/s, when the powerhouse was constructed. BPV for full load with 85m^3/s flow rate capacity was added in 2008. The work was carried out based on Yuba county requirement to maintain flow coverage for Chinook salmon (*Oncorhynchus tshawytscha*) and Steelhead trout (*Oncorhynchus mykiss*) at the downstream sections.

Figure 4.29 ***Drone footage of a retention basin with energy breakers in Switzerland, designed and operated to dampen hydropeaking waves*** (Source: Reuther Kristof)

The third type of measure is the **morphological solutions**. They are in situ solutions implemented at the river section downstream of the tailrace. They include **re-shaping riverbeds** to reduce dewatered habitats (i.e., creating pools) [4.86] and **creating habitats as shelters in side channels with stabilized flow levels** (similar to **creating embayment** and **shoreline habitat management** measures to address flow level fluctuations in reservoirs presented in Section 4.6.1). Hydropeaking can also lead to severe changes in the substrate at the recipient river section (e.g., facilitating the deposition of fine materials). In this case, **sediment management** measures can be taken to mitigate the conditions (presented in Section 4.4), which shall be combined with adequate flow releases (i.e., the concept of environmental flows) to sustain sufficient morphological conditions for the aquatic ecosystems.

Many relevant hydropeaking measures are also included and discussed in the European mitigation measure library [4.42].

4.6.4 REMARKS ON FLOW MANAGEMENT APPLICATIONS

Despite the increasing environmental concerns globally, it should be noted that in some cases, the flow management plans which intend to support fish within the reservoir or downstream are vague concerning nature in practice or not followed at all. In other instances, the operational protocol that supports fish may yield conditions that lead to artificial species selection of insensitive species. Hydropower operators may test **flow experiments with biological monitoring** to confirm the efficacy and inform adaptive management processes.

Limitations and considerations for flow management include but are not limited to water availability, temperature, habitat availability, species life cycle needs, hydropower scheduling needs, competing for water uses, seasonality, climate, and the hydropower plant's ability to divert or hold water for flows. With so many methods and trade-offs to consider, there is an urgent need for simplified decision trees for various cases to be developed to guide practitioners in setting adequate environmental flows for types of hydropower and evaluations of environmental flow efficacy and adaptive management. Further, there is a need for innovative tools and approaches to assist with scheduling water releases to optimize energy. Environmental outcomes, identify how and where the flexibility is within the flow constraints, and relate this information to plants that can provide such services.

4.7 Fishery Management and Other Similar Measures

The Roadmap provides an overview of the different measures in Section 4.2 to Section 4.6 to mitigate the main impacts of hydropower on aquatic ecosystems. In some hydropower projects or regions, such measures may not be adequate and require additional actions to ensure sustainable and viable fish populations. In these cases, fisheries management, compensation measures, or biodiversity offsetting might be needed to ensure healthy fish populations in the regulated watercourse [4.87]. Exemplary measures are presented for types in Table 4.5.

Table 4.5 ***Brief overview of fishery management techniques applicable at the water basin affected by hydropower regulation***

FISH MANAGEMENT			COMPENSATION MEASURES	BIODIVERSITY OFFSETTING
Fishery regulations	**Biological and chemical measures**	**Fish stocking***		
- Limit fishing quota - Limit fishing gear and type - Catch and Release fishing - Shorten the fishing season	- Control measures over aquatic species by using chemicals - Introduction of non-native species as prey animals*	- Re-introduction of native species - Release of hatchery fish (active breeding) - Release or implementation of fish eggs	- Restoration or creation of aquatic habitats - Sediment management with adequate flow releases	- Pollution control - Improving passage conditions at non-hydropower facilities - Control the spread and abundance of invasive species - Measures to mitigate the impact of climate change

* Not considered as a sustainable measure, therefore not recommended.

Given the complexity of the topics, it is beyond the scope of the Roadmap to cover all relevant aspects substantially. However, the document briefly introduces different measure types due to their potential importance in best practice management.

4.7.1 FISH MANAGEMENT

Fish management practices for caretaking fish populations have long traditions and are still active in several countries. Commonly, such measures address fish populations or their well-being rather than considering the local riverine ecosystem. They are particularly interested in regions with sport fishing species, like salmonids. Management types are sorted into three main categories. Fishery regulations, biological measures, and fish stockings.

Fishery regulations imply restrictions on fishermen on a given watercourse or sections. They include practices to **limit fishing quota** (e.g., limit number of rods per reach, bag limits in terms of species, size, and/or gender) or **limit fishing gear and type** (e.g., only fly fishing allowed or no gillnet fishing in lakes). Other regulations can only **determine 'catch and release'** fishing or **shorten the fishing season**.

Biological and chemical measures target fish populations indirectly. They consist of **control measures over aquatic species**, which are detrimental to native fish species. For instance, such measures can target fish parasites or invading species e.g., the extreme growth of aquatic vegetation (like macrophytes) that may alter the quality and abundance of fish habitats [4.88]. Such techniques may be implemented as chemical compounds (for instance addressing parasites). Contrary to control measures, **introducing non-native species as prey animals** have been used historically to improve the native population of predatory species. Due to its significantly uncertain ecological impact on the riverine ecosystem, this latter measure is not considered best practice and hence not recommended at all [4.42].

Fish stocking is the third type of measure in fishery management. It includes the **re-introduction of native fish species** through, for instance, **active breading** and release of native fish from a hatchery or by **artificial implementation** or **dispersal of fish eggs** in selected sites. Fish stocking is still a widespread technique for fishery management in regulated catchments. However, it is controversial in many regions as successful fish stocking in regulated watercourses may provide an undesired outcome in the long term (i.e., genetic side-effect) and hence worsen the status of wild fish populations. In addition, the fish stocking often focuses mainly on sport fishes and is less relevant for other species. Despite using native fish species, the artificially nursed fish likely have a low survival rate in the regulated watercourse during their different life stages. At the same time, they can also compete with wild individuals, which can be detrimental to the wild fish populations [4.89]. Fish stocking is not considered as sustainable measure and, therefore, is not recommended [4.42].

4.7.2 COMPENSATION MEASURES

The compensation measures commonly refer to habitat improvements on a larger scale. Therefore, they are not limited to the heavily regulated river only. Compensation measures can include **restoration or creation of fish habitats** (e.g., shelter habitats in side-channels of hydropeaked rivers) along the watercourse relevant for the native fish or at the river basin (within tributaries) by similar techniques presented in Section 4.3 (Figure 4.30). Measures also include **adequate sediment and substrate management** via similar practices discussed in Section 4.4.

Figure 4.30 ***Example of compensation measures in the Alps: river widening by reallocating embankments and restoring gravel bars in River Inn, Austria, to reduce the cumulative impact on fish communities in River Inn, financed by the hydropower plant owner.*** (Source: Jo Halvard Halleraker)

4.7.3 BIODIVERSITY OFFSETTING

Another alternative measure to improve conditions for fish populations in hydropower-regulated watercourses is **biodiversity offsetting**. It is a commonly complementary measure (i.e., integrated into a holistic approach) that aims to decrease the impact of other pressures on fish, principally to decrease the cumulative negative impacts on fish at the affected river basin. One type of measure is **pollution control** from agriculture and land use from the river basin to improve water quality. Other measures target connectivity for fish by removing non-hydropower barriers at the river basin or **improving passage conditions** at non-hydropower civil structures (e.g., road culverts). Further measures aim to **control the abundance and spread of invasive species** within the watercourse (including invasive fish, plant, or invertebrate species) by the mechanical removal of invasive vegetation and chemical or biological treatment (as presented in fish management to control parasites). Other measures **address the impact of climate change on native fish species**. Such practices are emerging in several regions, like planting riparian trees along narrow river sites to mitigate extreme water temperature increase from sun radiation. The exemplary concept is similar to restoring the riparian trees which may give other benefits (i.e., increase biomass of flora and fauna) presented in Section 4.5.1.

4.8 Integrated Solutions to Coordinate Hydropower Activities that Minimize Environmental Impact

Methods to address the impacts of hydropower activities on physical habitats, and consequently, on fish may require short- and longer-term solutions and maintenance efforts. Site-specific mitigation technology deployments or applications of models to support operational changes may have immediate, localized results. For example, supporting catchment scale restoration and management to reduce sediment input will typically involve a longer time frame. Still, it may help avoid some impacts or reduce their effects in areas impacted by hydropower. The holistic approach stands for basin or watershed-level planning and coordination, which can help to achieve environmental goals, especially in multi-reservoir systems.

Further, investing in and using tools can support decision-making, improve habitat assessments, measure and map habitat changes, and/or model development. This can improve understanding of choices and preferred outcomes and support efforts to avoid, minimize, and mitigate effects. The Roadmap highlights standard techniques to support local and watershed-level coordination of hydropower activities to mitigate their impact on nature.

Monitoring parameters along a watercourse can provide real-time data on both abiotic and biotic environmental processes. Recent developments in instrumentation technology have enabled more accurate measurements of water quality and quantity in more reservoir and river systems locations. Such instruments also utilize satellite or wireless communications, sending data streams to user interfaces in real time. Collected information on current conditions is the main input parameter for decision-support tools for sole or multi-reservoir management [4.90]. For detailed information on monitoring and characterization techniques, see Section 6.

The hydropower industry has long developed models to optimize power generation covering short to long-term scenarios. Other models have been developed to determine water quality and quantity metrics on local or catchment scales in the presence of hydropower actions. Another perspective targets habitat suitability. A significant European effort assessed river connectivity by creating a barriers database and examining fish macro-habitat suitability [4.51]. When these models are further developed, combining production targets with environmental constraints or goals will be the best approach. These models are usually site-specific and may be complicated by upstream dams changing their operations, or by extreme weather anomalies, due to climate change. Under normal conditions, the popular predictive models use hydrodynamic and water quality modules with optimization algorithms to determine maximum generation within any operation or water quality constraints. One common approach is that HPP operators develop site-specific predictive models to indicate when to release water and/or deploy technologies that support water quality and temperature targets. Development of similar conceptual models that examine how dams and other barriers affect aquatic habitat suitability and consequently alter the composition of aquatic communities is one method. This can allow an understanding of impacts and where to focus efforts for fish restoration, deployment of passage technologies, and guide hydropower development or dam removal.

Example: Aeration turbines are a type of mitigation for water quality and a 2015 survey of US industry identified 178 aeration turbines at 58 hydropower plants were in use for enhancing dissolved oxygen turbine discharges. Aeration turbines such as those deployed at the Osage project in Missouri, USA [4.91], may be turned on when site-specific models developed by owner/operators indicate there is risk to meeting water quality compliance targets.

The World Bank Group suggests several measures to mitigate hydropower impacts, including careful dam siting, design, operation, and provisioning of environmental flows or fishways. Additional recommendations for mitigation measures include restoring habitat, managing releases for cultural rituals, and offsetting impacts through actions such as river protection elsewhere in the watershed with similar biodiversity [4.60].

Cascade Hydropower Systems

Example: As an example, from the US mid-Columbia River system a saturation model was developed to predict the coordination of operational decisions that can mitigate impacts of supersaturation and incorporate these in a general multi-objective river, reservoir, and hydropower optimization tool [4.93].

It is challenging to apply similar models to catchments with several hydropower plants [4.92]. Advanced models can support the management of multi-reservoir water releases and even create a win-win for energy production and the environment. This requires complex research and modelling techniques with multi-objective optimization and forecasting tools. Moreover, coordinated operation between adjacent hydropower plants on the same watercourse can benefit the environment and the hydropower owners, ideally based on the transparent incorporation of stakeholders [4.94]. To optimize efficiency while coordinating water use, including environmental needs, the digitalization of hydropower is an emerging trend [4.95]. Therefore, it can lead to several benefits, maximizing energy generation and optimizing water management on a larger scale. Note: Details of the management of cascade hydropower systems can be found in the IEA Hydro Report Annex XIV report, *Management Models for Hydropower Cascade Reservoirs* [4.96].

4.9 Construction of New and Major Refurbishment of Existing Hydropower Plants

Section 3.3 covered the issues and risks posed by constructing new hydropower plants and redeveloping or refurbishing existing hydropower plants. Fundamentally, all new hydropower plants must meet any relevant requirements relating to the regulatory or licensing conditions of fish issues unless they do not impact fish habited river reaches (e.g., at high-altitude hydropower facilities). Similarly, this applies to any redevelopment and refurbishment work, including re-licensing. However, there are options for what is required to meet such requirements. This section of the Roadmap addresses some critical options for consideration.

For licensing new hydropower plants undergo an extensive study and design phase, including the fundamental components. This will identify issues and risks to fish, habitat, migration passage, and general well-being associated with the construction phase and operating regime. The main issues and risks posed by new construction can be characterized as impacts relating to maintaining fish connectivity and minimizing construction waste that contaminates water quality and increases turbidity.

Redevelopment of hydropower plants usually occurs after the facility has reached the end of its useful life or when it is necessary due to changed conditions (i.e., significant change in the local environment/climate or the need for adaptation to the modern electricity market). This tends to involve the removal of the old powerplant and the rebuilding and often expansion of a new one. As the original plant is often ancient and may not have considered issues associated with fish, the mitigation works will assume some of the challenges of a new build. However, this may be compromised by the layout of the original plant and the facilities and structures that may not be replaced. The main issues and risks posed by redevelopment would likely be similar, but probably lesser than those for new construction; impacts relating to maintaining fish connectivity and minimizing construction waste contaminating water quality and increasing turbidity.

Refurbishment of existing hydropower plants can range from significant overhauls of generating equipment to replacement. It can also cover retrofitting existing dams and reservoirs without hydropower facilities to utilize hydropower or the expansion of the existing powerhouse by adding more units. Structural works, such as expanding spillway capacity, can also be added to this category. Refurbishment's main issues and risks would likely differ from new construction or redevelopment. It is unlikely to involve stream flow diversions or significant construction waste. The most likely impact would be the curtailment or alteration of attraction flows as one or more units were taken out of service for lengthy periods.

4.10 Summary of Solutions

Mitigation measures naturally depend on the site and project-specific details of each case. From Section 4.2 to Section 4.6, various options are presented to address challenges. By the end of Section 4, all of the discussed options are listed in Tables 4.6 – 4.10 and organized according to the processes:

i.) Fragmentation
ii.) Impoundment
iii.) Sediment transport
iv.) Water temperature and quality
v.) Regulated flow and water abstraction

Note that the list duplicates a few measures when they offer viable options for different processes.

Figure 4.31 ***Mooserboden Dam and hydropower reservoir in Austria***
(Source: studio23/shutterstock.com)

Table 4.6 ***List of different measures to address the process i.) FRAGMENTATION. Note, that a few measures are duplicated in Table 4.6-4.10 as they apply to multiple processes***.

MEASURES	**CLASSIFICATION OF MEASURE TYPES**		**SUB-TYPE OF PROCESSES**
Vertical slot	Technical fishways	Volitional measures	Upstream fishway facilities
Pool and weir			
Trapezoidal			
Denil			
Nature-like bypass channels	Nature-like fishways		
Rock ramp			
Passage for climbing species			
Fish lifts/lock and pump		Non-volitional measures	
Trap and Transport (Collection systems)			
Alden turbine	Ecologically Improved Turbines	Conveyance measures	Downstream fishway facilities
Minimum Gap Runner			
DIVE turbine			
Restoration Hydro turbine			
Very Low Head turbine			
Total or Partial turbine shutdown	Ecologically Improved Operations		
Weir or spill overflow			
Early warning systems			
Navigation lock passage			
Fine screens	Physical barriers	Screening (or shielding) and guidance	
Rotary screens			
Eicher screens			
Modular Inclined screens			
Coanda screens and other bottom-type intakes			
Barrier nets			
Fish Guidance Racks with small bar spacing			
Fish Guidance Racks with wide bar spacing	Mechanical and behavioural barriers		
Skimming walls			
Hybrid barriers			
Light	Sensory and behavioural barriers		
Sound			
Air curtains			
Electricity			
Surface collection pipes	Collection systems		
Barrier nets with T&T			
Fish pumps and lifts			
Trap and Transport			

Table 4.7 ***List of different measures to address the process ii.) IMPOUNDMENT. Note, that a few measures are duplicated in Table 4.6-4.10 as they apply to multiple processes***.

MEASURES
Artificially created bypass) channels
Storage level reduction (ORM)
Manage shoreline/shallow habitats (ORM)
Enhanced lateral connectivity
In-channel habitat improvement
Creation or restoration of habitat in tributaries
Reduction of vegetation

Table 4.8 ***List of different measures to address the process iii.) SEDIMENT TRANSPORT. Note that a few measures are duplicated in Table 4.6-4.10 as they apply to multiple processes***.

MEASURES
Sediment flushing
Mobilizing flows
Dredging
Re-introduction of sediments (passive)
Re-introduction of sediments (active)
Introduce sediments downstream (feeding)
Restoring the lateral erosion process
The mechanical breakup of armoured riverbeds & adequate flow releases
Catchment scale sediment management

Table 4.9 ***List of different measures to address the process iv.) WATER TEMPERATURE AND WATER QUALITY. Note that a few measures are duplicated in Table 4.6-4.10 as apply to multiple processes***.

MEASURES	SUB-TYPE OF PROCESSES
Adding gravel bars	Temperature and stratification
Restoring the lateral erosion process	
Restoring riparian trees or reservoir trees	
Increase inflow from the upper reservoir(s) (ORM)	
Intakes with flexible sill level or with multiple level configurations	
Catchment scale nutrient management	Nutrient loads and further chemical changes
Remove the top silt layer of sediments (ORM)	
Create a smaller reservoir upstream	
Sustain or improve conditions for native filter-feeding organisms (ORM)	
Mechanical reduction of macrophytes (ORM)	
Surface aeration technologies (ORM)	
Hypolimnetic aeration (ORM)	
Increase inflow from the upper reservoir(s) (ORM)	
Self-aerating turbines	
Cautious operation of reservoirs (ORM)	
Water is withdrawn from above the oxycline	
Flow deflectors at spillways	Supersaturation
Operational measures at the hydropower plant	
Modified power station design and operating regime	
Retrofitted creek intakes (vacuum gates)	
Air detrainment devices	
Maintain clean trash-racks and control discharge at the creek intakes	

Table 4.10 ***List of different measures to address the process v.) REGULATED FLOW AND WATER ABSTRACTION. Note that a few measures are duplicated in Table 4.6-4.10 as they apply to multiple processes***.

MEASURES	CLASSIFICATION OF MEASURE TYPES		SUB-TYPE OF PROCESSES
Deployment of fish exclusion technologies			Inter-basin transfer
Limit water abstraction from the donor basin			
Create embayment			
Create embayment		Water level management in reservoirs	Sub-watershed regulation
Manage shoreline/shallow habitats (ORM)			
Limit water abstraction from the donor watercourse			
Increase inflow from the upper reservoir(s) (ORM)			
Artificial floating islands (ORM)			
Enhanced connectivity to tributaries (ORM)			
Minimum flow requirement		Water level management downstream in bypass sections (Flow management plans)	
Instream flow requirement			
Environmental flow (e-flow)			
Gradual ramping with thresholds	Operational measure	Water level management downstream from hydropower tailrace (hydropeaking mitigation)	
Reduction of discharge extremities			
Reduction of peaking frequency			
Increase of base flow (following the concept of environmental flows)			
Adaptive hydropeaking			
Retention basin	Constructional measure		
Man-made channel for high discharge flows			
Relocate hydropower tailrace			
By-pass valves			
Re-shaping riverbeds	Morphological measure		
Creating habitats in side channels & stabilized flow levels			
Sediment management & adequate flow releases			
Testing flow release strategies with biological monitoring			

SECTION 5: DECISION-MAKING PROCESSES

Fundamentally, all challenges identified for a new or existing hydropower project must be addressed, and proposed solutions must meet regulatory requirements. However, there are many ways to achieve this, as presented in Section 4. How to choose between competing options is the theme of **Section 5**. The process must be expanded beyond economic considerations (See Section 5.2) to include relevant non-economic considerations. To enable these choices, the Roadmap presents flowcharts as a "pictorial" tool that follows or guides the process but does not make the decisions themselves. The flowcharts (Section 5.5) are a dedicated component that makes the Roadmap more user-friendly. A fictional case study using a series of flowcharts can be found in the **Appendix** (available separately).

5.1 Approach to Address the Majority of the Known Challenges

The main challenges for fish in rivers with hydropower developments are generally well-known. They can be distributed in the following categories:

- Reduced connectivity in upstream and downstream directions, which limits fish migratory pathways and hence access to valuable habitats to fulfil the life cycle.
- Alterations in natural flow regimes and flow depletion. This applies to the river downstream of hydropower plants, bypasses, and diverted river reaches [5.1]. Flow alterations and challenge are included in both short and long-term timescales.
- Habitat modification and fragmentation. This category applies to river sections upstream of the dam turned into ponds and lentic habitats, as well as downstream and bypassed sections. Habitat changes can occur due to changes in flow quantities and qualities and transported materials (e.g., sediment), both upstream and downstream of the hydropower plant.

Before considering mitigation, the initial step is to investigate if any challenges to fish are present. This step combines methods, including site and literature surveys, physical and/or various modelling techniques, and data analysis. The purpose is to investigate the degree of impact the challenges are causing on the fish population. This is the diagnosis phase; the actual status of the fish population should be compared to a reference or target. This could be a natural population, contributing to the “good ecological potential” described by the European Water Framework Directive or other restoration objectives. Finally, suitable mitigation measures must be planned, implemented, maintained and monitored adaptively.

5.2 Cost-benefit, Cost-effective, and Multi-Criteria Decision Analyses for Mitigation Measures for Fish

Even though the Roadmap presents various challenges hydropower poses to fish communities, its main concern addresses fragmentation. These should be followed where regulations are prescribed to address the impact of hydropower on fish. However, in many hydropower development projects, there are several options to choose from to meet the regulatory framework. In these cases, the use of economic methods can be adopted. Economic considerations in decision-making are introduced in this section. However, the presented concepts can also be applied to measures that address other challenges besides fish migration past hydropower facilities.

5.2.1 BACKGROUND

When a hydropower barrier closes off a free-flowing stream, choices may have to be made regarding passing fish safely past that barrier. In some circumstances, decisions are defined based on regulations.

However, there are some situations where other factors, like economic decisions, are appropriate to support mitigation or restoration measures selection.

A lack of data can make decision-making processes difficult to support managers when selecting mitigation measures. There are several options to provide a safe and effective means to remedy this. This section will cover the following options:

- The types of economic valuation processes that are suitable and how to select the most appropriate for any given situation (Section 5.2.2).
- Types of decision-making methods include economic valuation processes and when it is appropriate to use them (Section 5.2.3).

Example: A recent study of the FIThydro project collected costs of building, maintaining and monitoring fish passage measures using 327 case studies (Germany: 151, Austria: 101, Sweden: 58, France: 16, Switzerland: 1). The data was available through reports and questionnaires sent to European hydropower operators and available online data. The objective was to collect the data to support decision-makers providing information about the cost trade-off between fish passage restoration and hydropower production. Results showed that nature-like solutions for the fish pass were less costly than technical solutions, and they incurred fewer power losses. Comparing the costs categories found that construction was the largest share of operation and power losses. However, under a high electricity price scenario, power losses exceed construction costs for technical fish passes. The authors highlighted the need for more data for operational, power loss, and monitoring costs associated with passage measures. They recommended standardizing the methods for monitoring and reporting data to help policymakers with recommendations [5.1][5.2].

5.2.2 TYPES OF ECONOMIC VALUATION

Despite data availability, a set of models and tools can be used and applied to support decision-making. Providing an economic valuation can be seen as a process to determine the worth of a subject of interest (e.g., an abundance of fish species, flood protection role of hydropower, among others) to local people or the society in general [5.3]. Therefore, managers could benefit from this approach as it provides valuable input for selecting measures or actions to reduce, restore or prevent any environmental impact that hydropower production might have on the watercourse (e.g., the decline in fish populations, effects from fish barriers, among others).

The practical application of economic valuation for the good or service to be valued can be described as a three-step process:

A. **Qualitative assessment** requires assessing the baseline level of environmental quality and comparing it with the possible changes from the proposed mitigation measures.

B. **Quantitative assessment** includes inputs from actual data or modelling; different indicators could be used accordingly, for example, to quantify physicochemical quality, ecological quality, degree of improvement, or quality declination.

C. **Economic assessment** is carried out to estimate the monetary value of the change of the good or service. There are three primary types of economic valuation methods:

a. Market prices, when goods or services can be associated with markets where money is traded off for purchases of goods and services, price data are used to estimate economic value.

b. Revealed preference methods apply to goods and services that cannot be traded in the market. However, their characteristics affect the demand for other goods and services (e.g., the travel cost method can be used as how much the value of the recreational benefit of the trip or hedonic property pricing can be used from the property market such as how much will the price change from being close to a green area).

c. Stated preference methods used questionnaires and hypothetical markets to trade-off money since many natural resources are not traded in markets. Those environmental goods and services such as healthy macroinvertebrates or fish populations that are not traded in the market and do not have an overvalued monetary value are difficult to be evaluated economically. Thus, they are often undervalued by society. For example, contingent valuation and choice experiments are the most applied methods through the *Willingness to pay* method. Respondents are given choices involving different costs and asked to choose their favourites.

Therefore, revealed preference and stated preference methods are the two techniques used to conduct an economic valuation of goods and services with non-market value.

The loss of ecosystem services due to hydropower development should be part of the economic valuation. The Mapping and Assessment of Ecosystems and their Services framework are recommended as a starting point for considering this process.

Regardless of the type of economic assessment applied, there are some limitations and challenges that need to be considered together with recommendations:

- Possible bias through the process of interviewing.
- Limitations related to how to monetize changes that are not reversible.
- Address the time (discounting of cost and benefits) and the uncertainty from monetization during the decision-making process.
- Avoid excluding impacts that are difficult to monetize (highly recommended).
- Keep the process transparent (highly recommended).

Value transfer can occur when constraints make it challenging to carry out a primary economic valuation of the above method. It is a more straightforward and less accurate method but can be used when an economic valuation is needed. Value transfer, also known as "benefits transfer." Although it sounds like a simple method, it is essential to consider the followings:

- There is a need for competent source studies with relevant non-market values to assess relevant benefits and costs.
- It requires statistical techniques to adequately adjust the differences between the settings with the original values and the ones used.

The following flowchart (Figure 5.1) guides the reader toward appropriate non-market values for the management options.

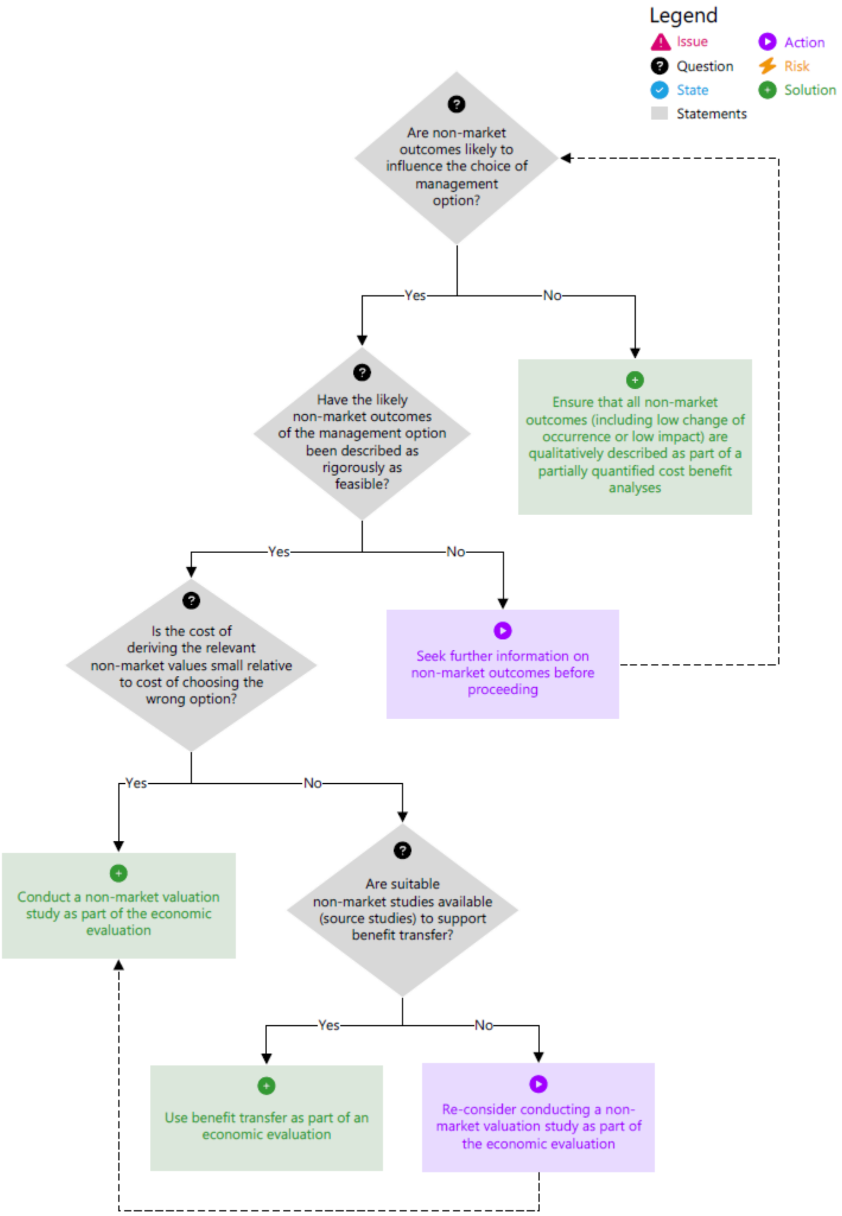


Figure 5.1 ***Manage non-market value outcomes in policy analysis*** (Modified from [5.4])

Once an economic valuation for market and non-market values are assessed, these data can be used as inputs for Cost-benefit, Cost-effective, and Multi-Criteria Decision analyses. Section 5.2.3 covers which method would be more appropriate for mitigation measures for fish.

5.2.3 TYPES OF ECONOMIC DECISION-MAKING METHODS

Several types of economic decision-making methods can be found in the literature. In this Roadmap, the following three are considered: Cost-benefit analyses (CBA), Cost-effective analyses (CEA), and Multi-Criteria Decision Analyses (MCA, also commonly referred to as MCDA), and combinations of these.

The principal difference between CBA and CEA is that in the CBA method, all costs and benefits are valued and compared based on their cumulative present values (Figure 5.2). The decision rule is simple if the Net Present Value (NPV, which is the present value of benefits minus the present value of the costs) is positive, benefits exceed the costs of the project or policy assessed, increasing the social welfare according to Kaldor-Hicks criterion [5.5]. In the CEA, outcomes are measured in some natural one-dimensional unit that can be assessed through qualitative or quantitative methods. It helps determine the least cost, e.g., mitigation measure of achieving a specified objective or target. MCA is useful when several criteria need to be considered. CEA and CBA can be combined or part of the MCA. In addition, when the economic valuation can be complicated to be carried out with an economical assessment or when the impacts are difficult to quantify, MCA can include stakeholders' or panel expert opinions, which can be included as weighing or preferences values. It also needs to be considered that this could compromise the quality of the analyses.

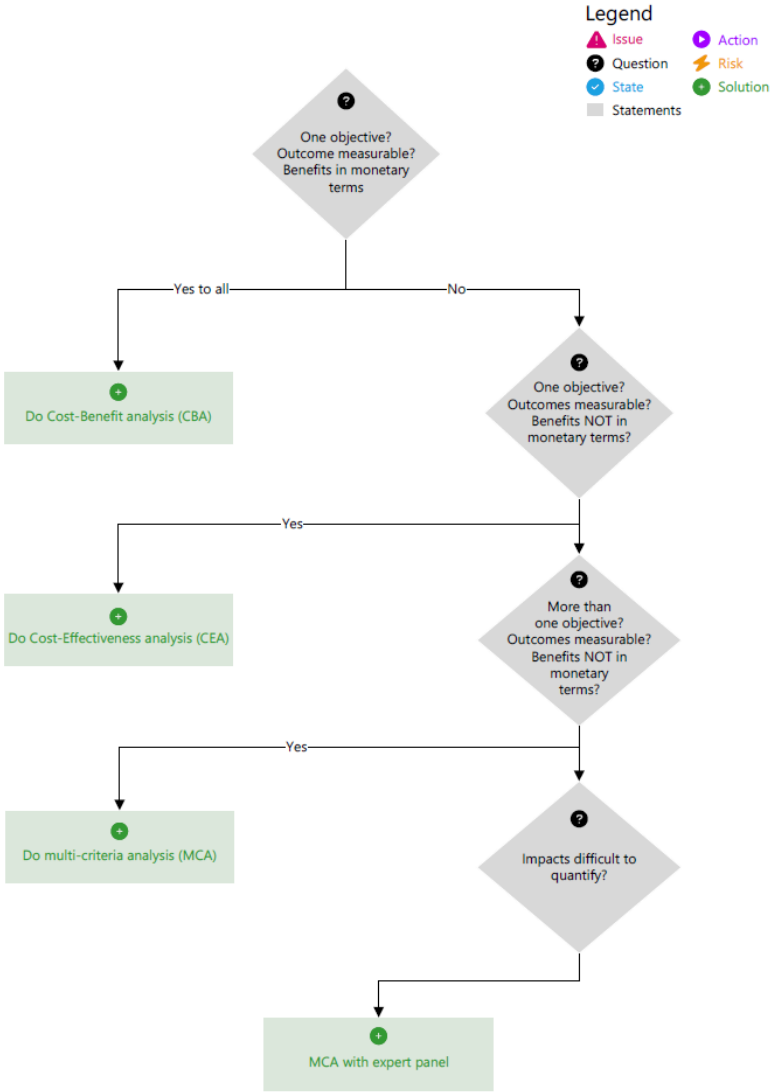


Figure 5.1 ***Flowchart guides selecting CBA, CEA, and MCA methods*** (Source: [5.6])

CEA is a valuable alternative to CBA in areas where benefits cannot be quantified monetarily to compare alternative mitigation options to identify the option that can reach a well-defined objective most cost-effectively [5.7]. However, CEA is often not a standalone tool for decision support. The benefits are defined only in one dimension (e.g., cost-effectiveness). The primary analysis does not consider other dimensions such as equity, feasibility, or co-benefits. Still, they could be considered during the selection process of the chosen options.

Once the method has been selected, each method requires different steps to be carried out, as summarized in Table 5.1.

Table 5.1 ***General steps through the CBA, CEA, and MCA methods as summarized in [5.8].***

STEP	CBA	CEA	MCA
1.	Participation (engage and consult with key stakeholders throughout the CBA process).	Frame the study (objectives, key parameters).	Identify the problem and conduct stakeholder workshops to establish operationally meaningful definitions of criteria and the alternatives to be evaluated.
2.	Identify the problem.	Characterize the study (Specify the base case, the "do nothing" scenario).	Comparative evaluation of alternatives in terms of each criterion, preferably emphasizing the importance of gaps between alternatives.
3.	Identify baseline and alternative scenarios (including maintaining current arrangements).	Identify and specify costs and avoid costs (costs, benefits, and externalities).	Assessment of importance weights by careful consideration of the ranges of outcomes on each criterion.
4.	Draw the boundaries: decide whose costs and benefits count (stakeholders affected).	Analyze and report incremental costs (compare the options, consider the uncertainty, and conduct sensitivity analyses).	Application of one or more methods for aggregating preferences or outranking the alternatives.
5.	Identify the physical impacts of each alternative (data gathering, analysis, and modelling activities).		The subjection of aggregated values to sensitivity analysis.
6.	Identify the costs and benefits of each alternative. Identify the full range of impacts of the alternatives.		
7.	Monetize impacts (monetize costs and benefits).		
8.	Discount future costs and benefits to obtain present values. Specify why selecting the discount rate.		
9.	Analyze distributional impacts for selected groups or communities: equity. Consider and discuss the incidence of costs and benefits.		
10.	Calculate the net present value for each option. Note the outcome (positive or negative NPV) alongside other significant non-monetized costs and benefits.		
11.	Sensitivity Analysis assesses potential uncertainties and biases in the analysis, including discount rates and other key assumptions.		
12.	Review/conclusion (consider external review).		

Regardless of the method applied, there is a need to identify key parameters or indicators to evaluate the outcomes from the different mitigation measures and compare the alternatives with the baseline situation. The following aspects must be considered in evaluating which mitigation measure will be more cost-effective or cost-beneficial to mitigate impacts from hydropower on fish.

Physical or biological data can be used to determine the measure's effectiveness. Field measurements and monitoring techniques for data collection are discussed in Section 6. However, it is important to determine which mitigation measure is more adequate, considering social, ecological, and economic factors, before selecting one. This can lead to data from literature or another site, which increases the uncertainty of the decision.

In addition, modelling can simulate the effects of implementing the measures and combine this with data from the literature. Uncertainties from modelling should also be considered, and the lack of validation if the alternatives are hypothetical solutions or mitigation measures. Qualitative data can be used when quantitative data is unavailable, as well as the stakeholder's opinion, which is possible in the MCDA method.

Examples using the three techniques are provided in the **Appendix** (available separately).

5.2.4 USE OF RISK-BASED ASSESSMENT METHODS

In general terms, an environmental risk assessment (ERA) evaluates how likely the environment may be impacted due to exposure to one or more environmental stressors. An ERA is a tool or methodology, that can contribute to the broader and more comprehensive process of the EIA (Section 2.5). Environmental risk deals with the probability of an event causing a potentially undesirable outcome. Quantitative risk assessment is a function of probability (the mathematical measure of risk) and consequence (determining the nature of the undesirable outcome). The application of risk assessment techniques to fish is usually termed "ecological risk assessment." Ecological risk assessment is a fundamental tool used for informed decision-making. However, for this Roadmap, based on *providing best practices for managing fish and hydropower facilities,* the use of any risk-based assessment method, while strongly encouraged, is considered too complex to be included in this section on decision-making.

5.3 Flowchart Structure

The Roadmap generally presents the impact of hydropower utilization on freshwater fish communities. The described challenges and the practices to address them efficiently are summarized through a multiple-layer flowchart in the following subsections, which form the core of decision-support provided by the Roadmap. Such an approach provides a simple yet helpful tool to the reader to enhance sustainability at any given site regulated for hydropower purposes and support the decision-making of mitigation options.

The first layer of the flowchart (Charts 1.1 and 1.2) informs the reader about the complexity of addressing environmental challenges from hydropower regulations. The problems are presented as challenges and arranged according to the status of the hydropower scheme of interest. At the same time, the need for mitigation program(s) at the site is addressed. Existing hydro projects mainly define the actions. The Roadmap also addresses projects in the planning or construction phase.

The second layer (Charts 2.1 to 2.8) is organized according to the challenges. Following the five processes introduced in Section 3.2, each has one or several individual flowcharts at this level. The charts navigate the reader to the recommended best practices for consideration, which either are limited or endorsed by the main abiotic and biotic conditions. The Roadmap at all layers corresponds with the described content on fish and hydropower interaction and practices from Sections 3 and 4.

5.4 How to use the Roadmap

Each flowchart has three roles.

1. **To underline the importance of knowledge** of local conditions (e.g., information on fish, water quality and quantity, sedimentation, among others) in regulated rivers at specific locations.
2. **To identify fish communities' main challenges** (issues: defined as a challenge which will occur; and risks: defined as a challenge which may occur) based primarily on site and scheme-specific information.
3. **To guide the reader towards best practices** to overcome potential challenges. Jointly they serve as an effective tool for decision-making by the reader.

The Roadmap also requires information on governing biotic and abiotic conditions at the hydropower site of interest. Sustainable hydropower development requires information on geological and hydrological conditions, operational modes, and mitigation measures. Information on fish species, their habitats, and how they are affected or threatened by the hydropower facilities are also required.

It is suggested that the reader starts at the **first layer** of the Roadmap, as indicated in **Charts 1.1** and **1.2**. Following the lines, the reader is led to check the status of the hydropower project. At an existing plant, or one that is planned or under construction, the user is navigated towards ecological (*A*) and technical characterization (*B*) and the effect of the latter on the former one (*C*):

A. The ecological perspectives are formalized around biodiversity knowledge, focusing on fish communities affected or threatened by existing or planned hydropower regulation. Ecological aims (values) follow ecological, economic, and social features.

B. Hydropower scheme characterization requires basic details about the governing environment of the hydropower plant, its operation modes, and the area affected by river regulation. Based on such information, the reader will be navigated through the eight flowcharts on the second layer.

When the path on the second layer of flowcharts crosses any ***Issue*** or ***Risk,*** it always leads the reader to address them by one or several measures. At the same time, the reader must also proceed to step C on the first layer. Note: every hydropower project presents some issues already by its presence (e.g., fragmentation).

C. It is case-specific to identify whether a specific challenge harms the fish communities. In other words, to decide whether one identified potential challenge needs to be further addressed by mitigation measures or not. Accordingly, the reader is directed towards an Impact Assessment (addressed in Section 2.5 and Section 2.6) in which an investigation of the current conditions (or conditions in the future at new projects) on the target fish species is needed. Based on the impact severity on the fish community (result from the Impact Assessment), the outcome of the investigation can vary as follows:

    a. None, or extremely low severity.

    b. Moderate or High severity,

    c. Unknown severity.

Except for case *a.*, the challenge of interest must be addressed further. Regarding *what to do* in such a situation, the reader is guided to the second layer of the flowchart.

The **second layer** of the flowchart (**Charts 2.1** to **2.8**) guides the reader to find best practices for all identified challenges which must be addressed. The required information remains similar to the first layer to use the flowcharts further. Hence, site-specific information on abiotic and biotic conditions is used to navigate the reader toward the right tools and methods to address any problems. The reader is advised to address the problems one by one; therefore, the challenges and their associated practices are presented in separate charts as follows:

Chart 2.1 – Fragmentation (upstream migration)

Chart 2.2 – Fragmentation (downstream migration)

Chart 2.3 – Impoundment

Chart 2.4 – Sediment management

Chart 2.5 – Temperature and stratification

Chart 2.6 – Nutrients and O_2 content

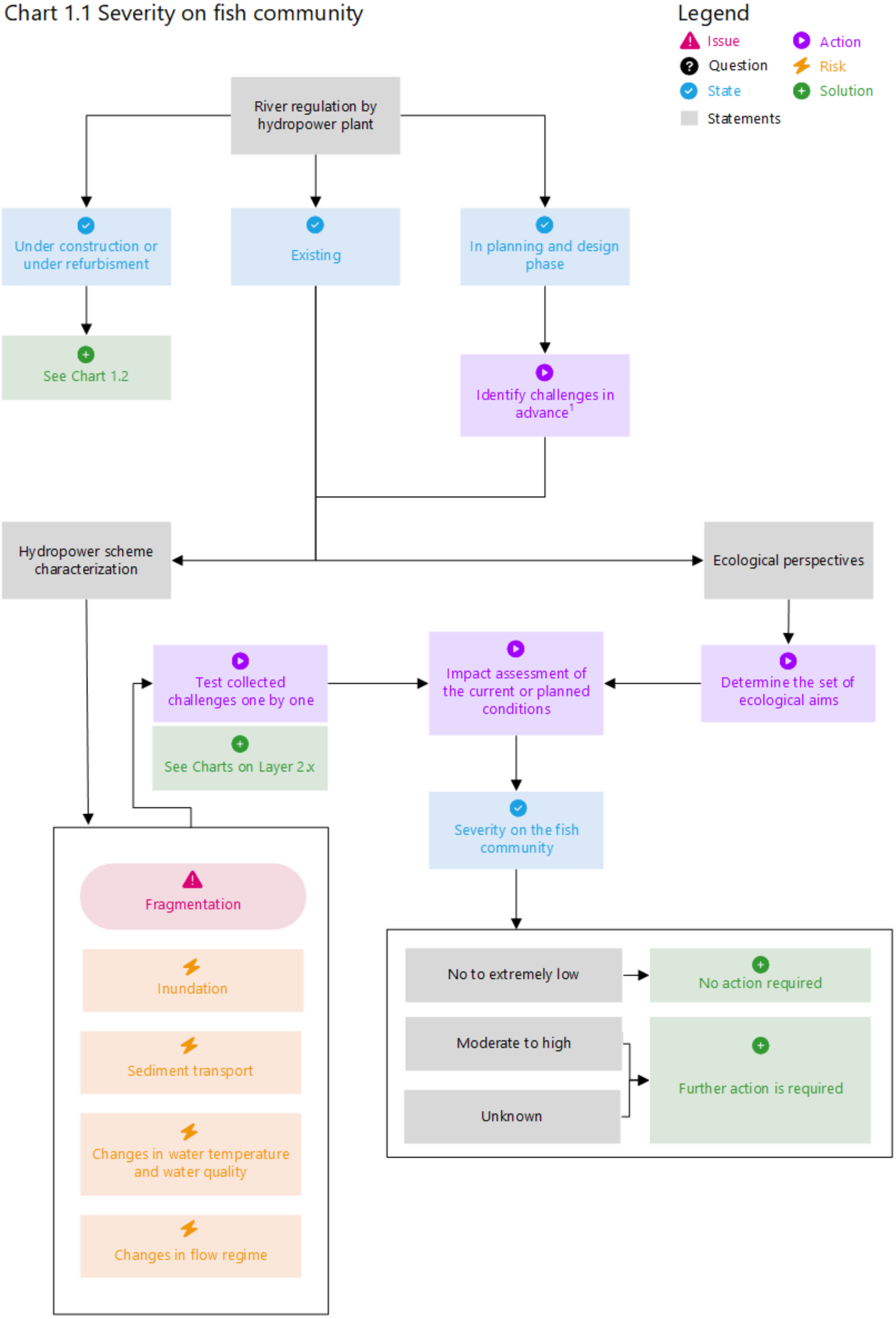
Chart 2.7 – Supersaturation

Chart 2.8 – Flow regulation and water abstraction

The use of flowcharts is demonstrated with a fictional case history in the **Appendix** (available separately).

5.5 Decision Trees (Multiple Layer Flowcharts)

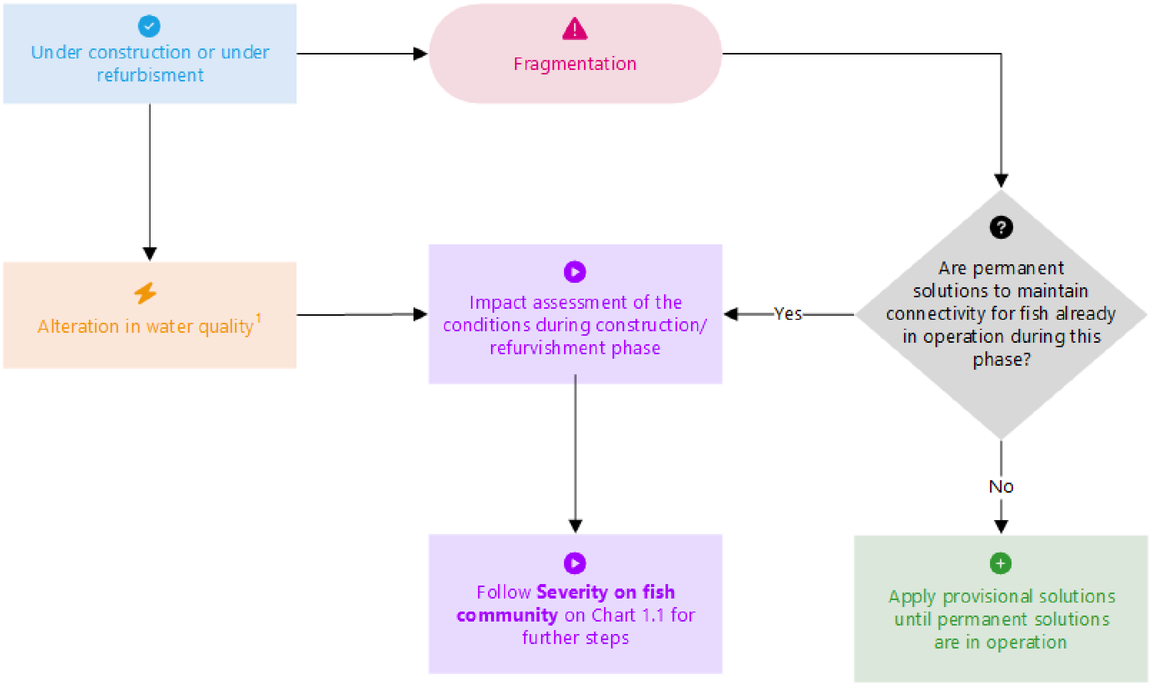
Chart 1.1 Severity on fish community



Notes

[1] Governing conditions which can cause conflicts with fish society can be identified in the planning phase based on the known charecteristics of the hydropwer scheme.

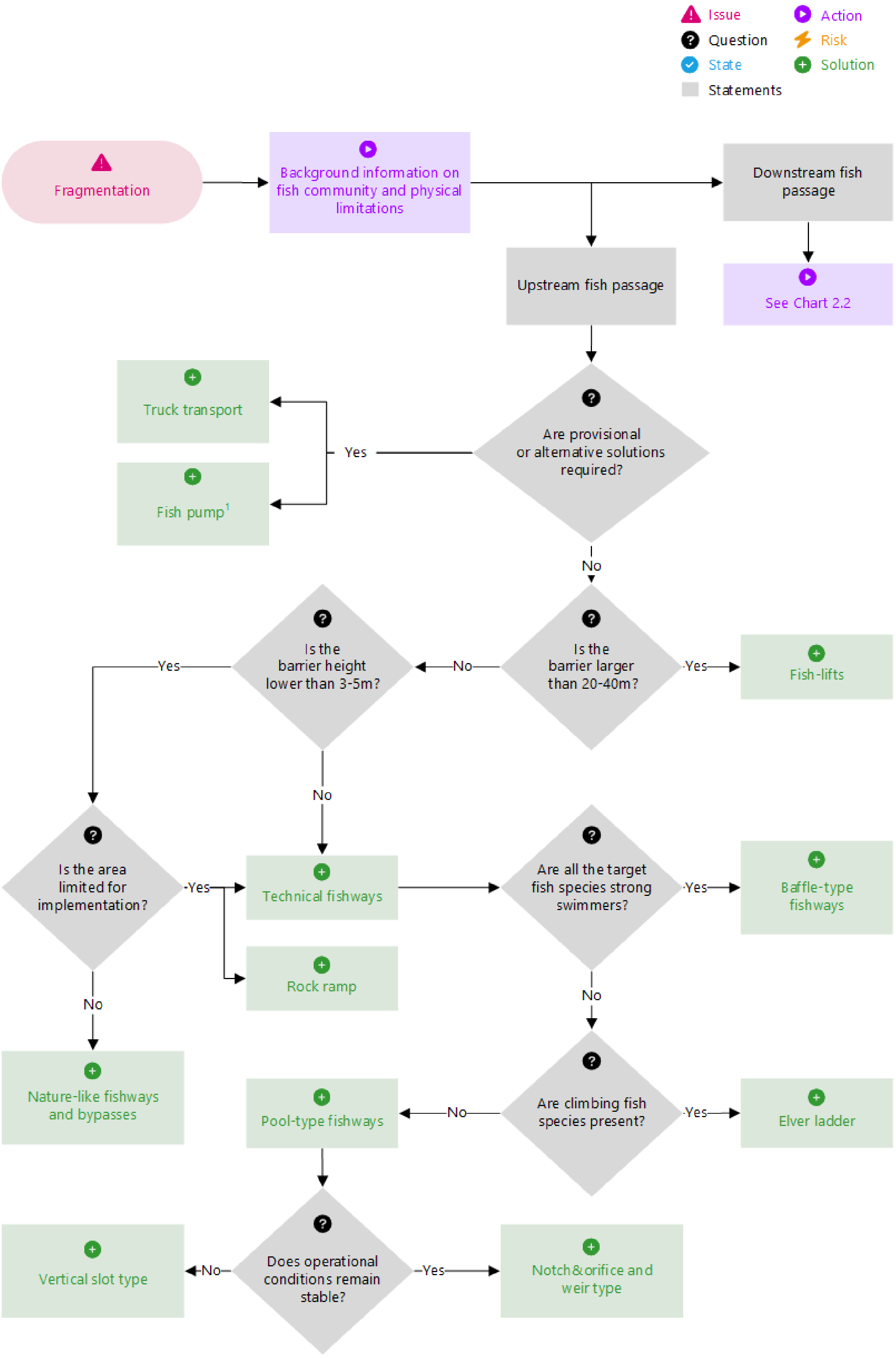
Chart 1.2 Hydropower plant under construction or refurbishment



Notes

[1] Temporary contamination mainly due to the onsite fabrication of structures

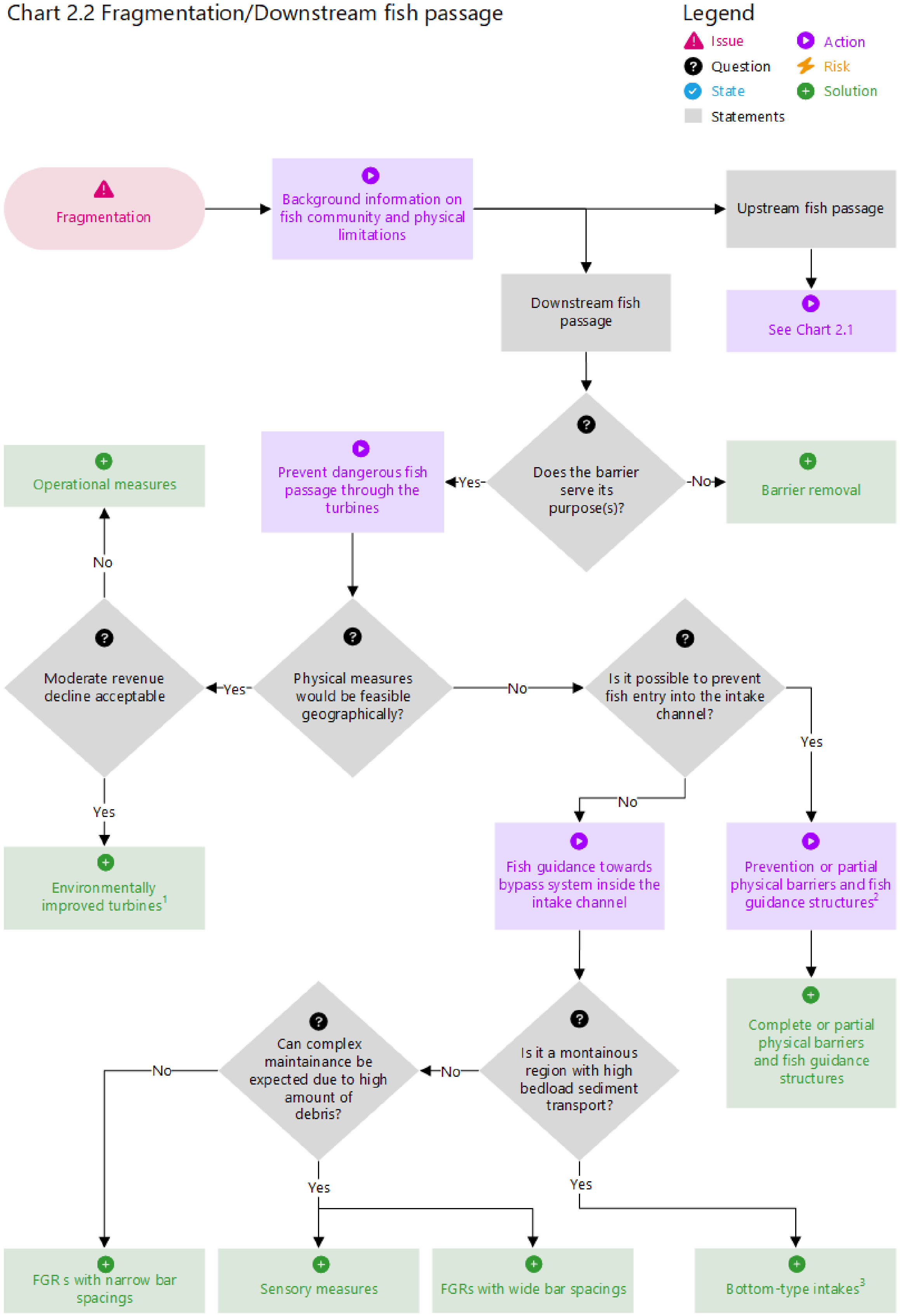
Chart 2.1 Fragmentation/Upstream fish passage



Notes

[1] Only recommended if the target fish are only long migratory species in adult life stage

Chart 2.2 Fragmentation/Downstream fish passage



Notes

[1] Recommended for low-head hydropower schemes up to 15-30 m head differences. See section 4.2.5 for further information.

[2] As physical barriers, barrier nets are considered, while floating fish guidance booms and racks are considered as fish guidance structures.

[3] Recommended only at low operational discharges

Chart 2.3 Inundation

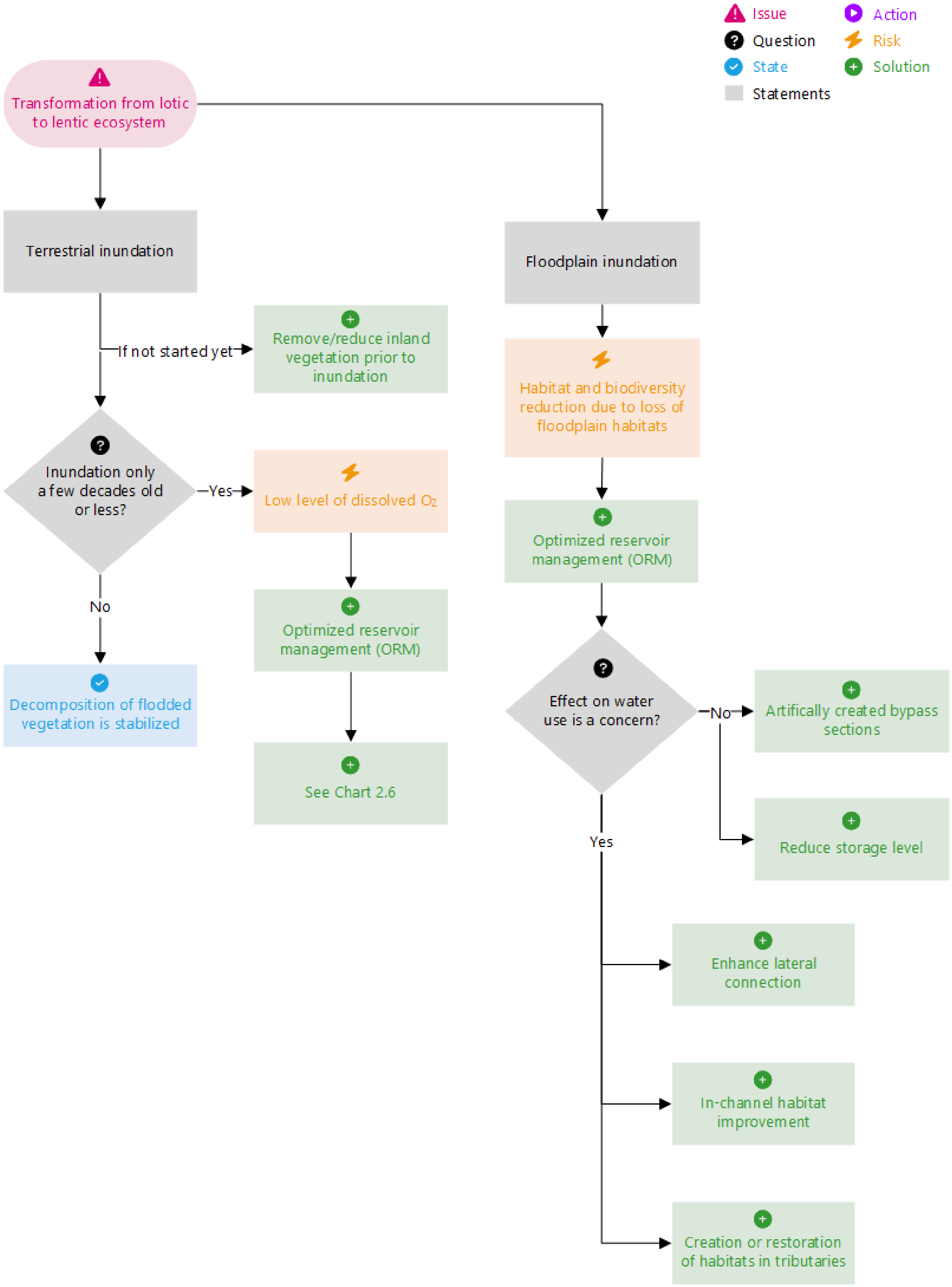


Chart 2.4 Sediment management

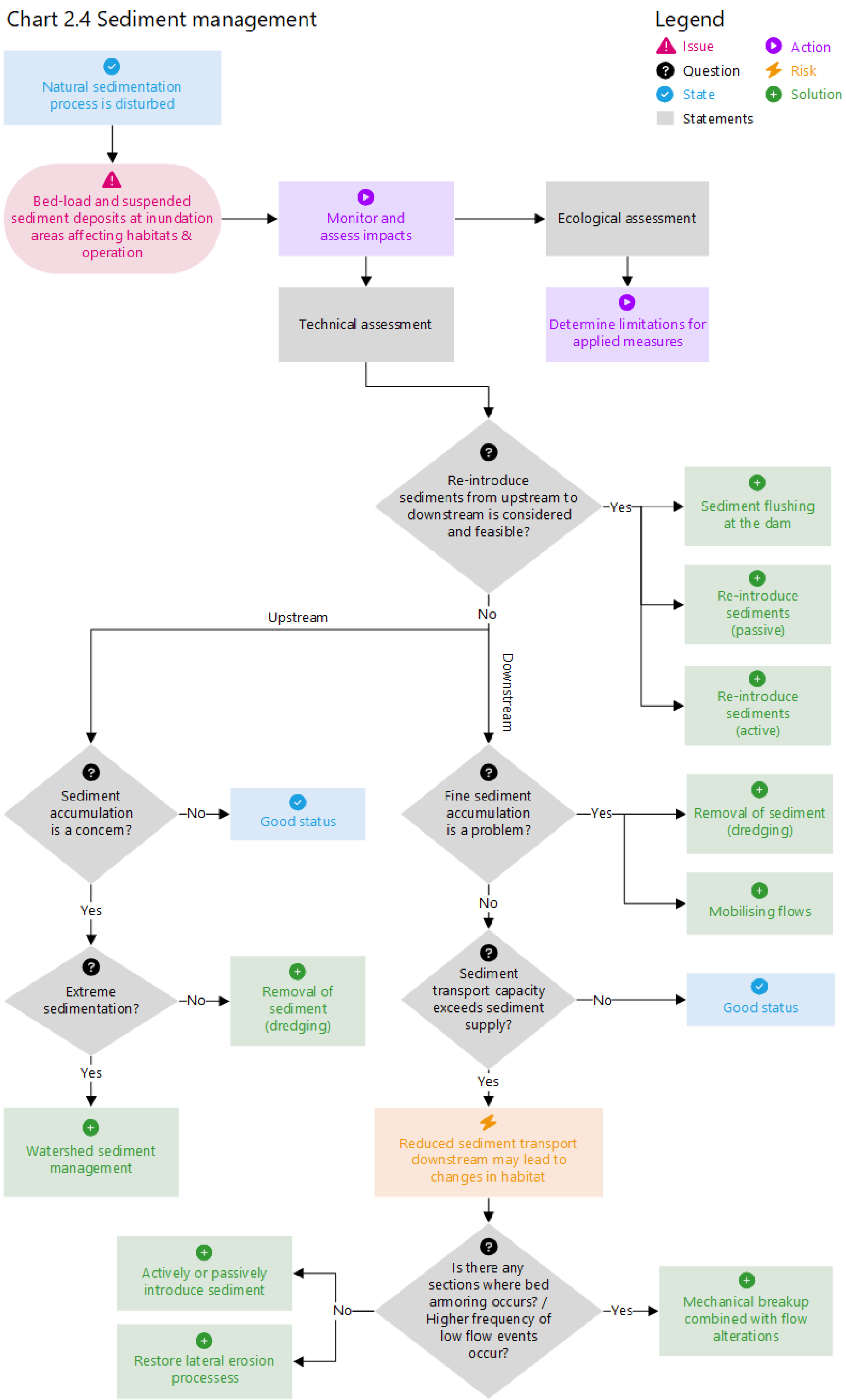


Chart 2.5 Temperature & stratification

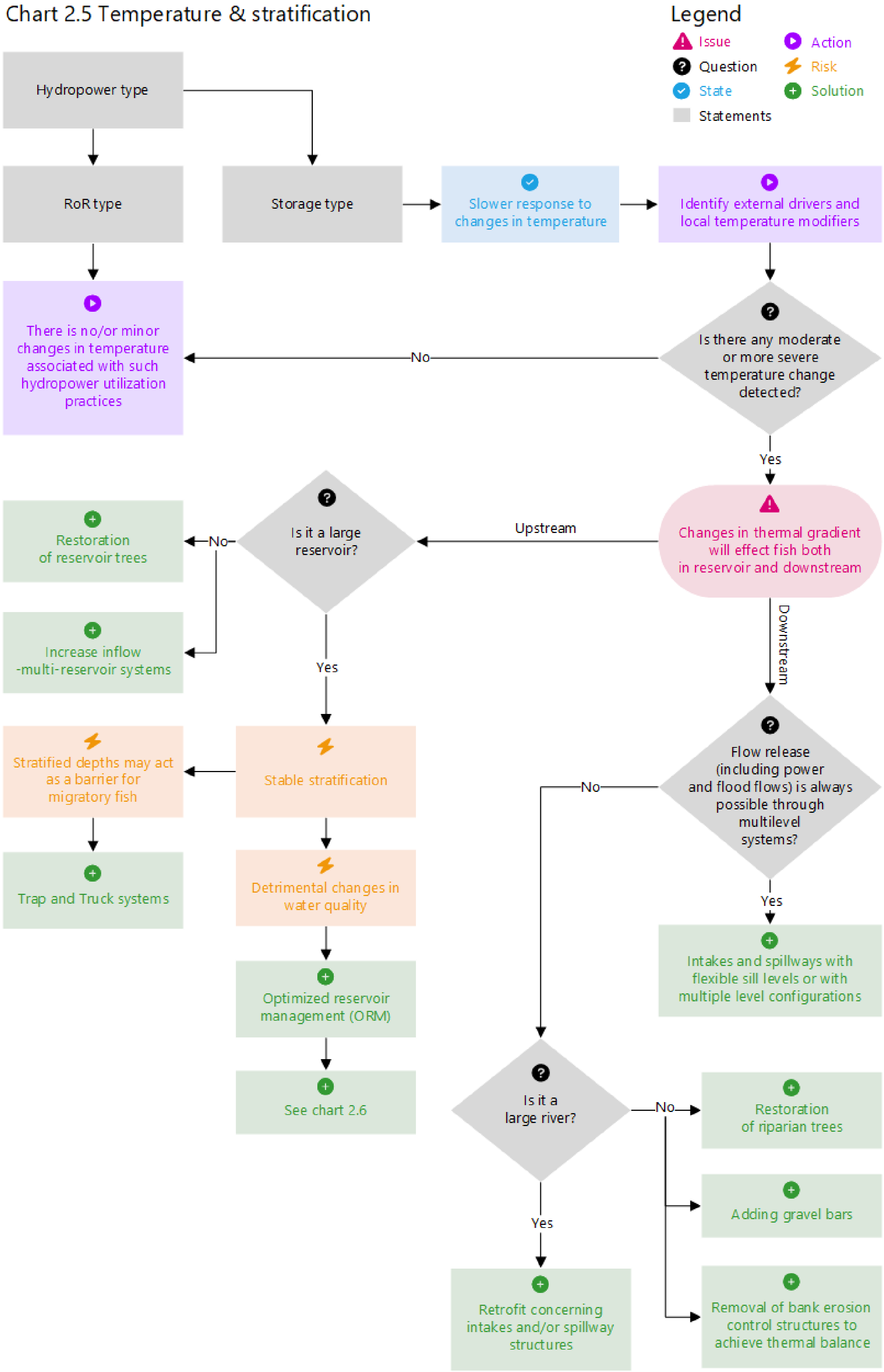


Chart 2.6 Nutrients & O_2

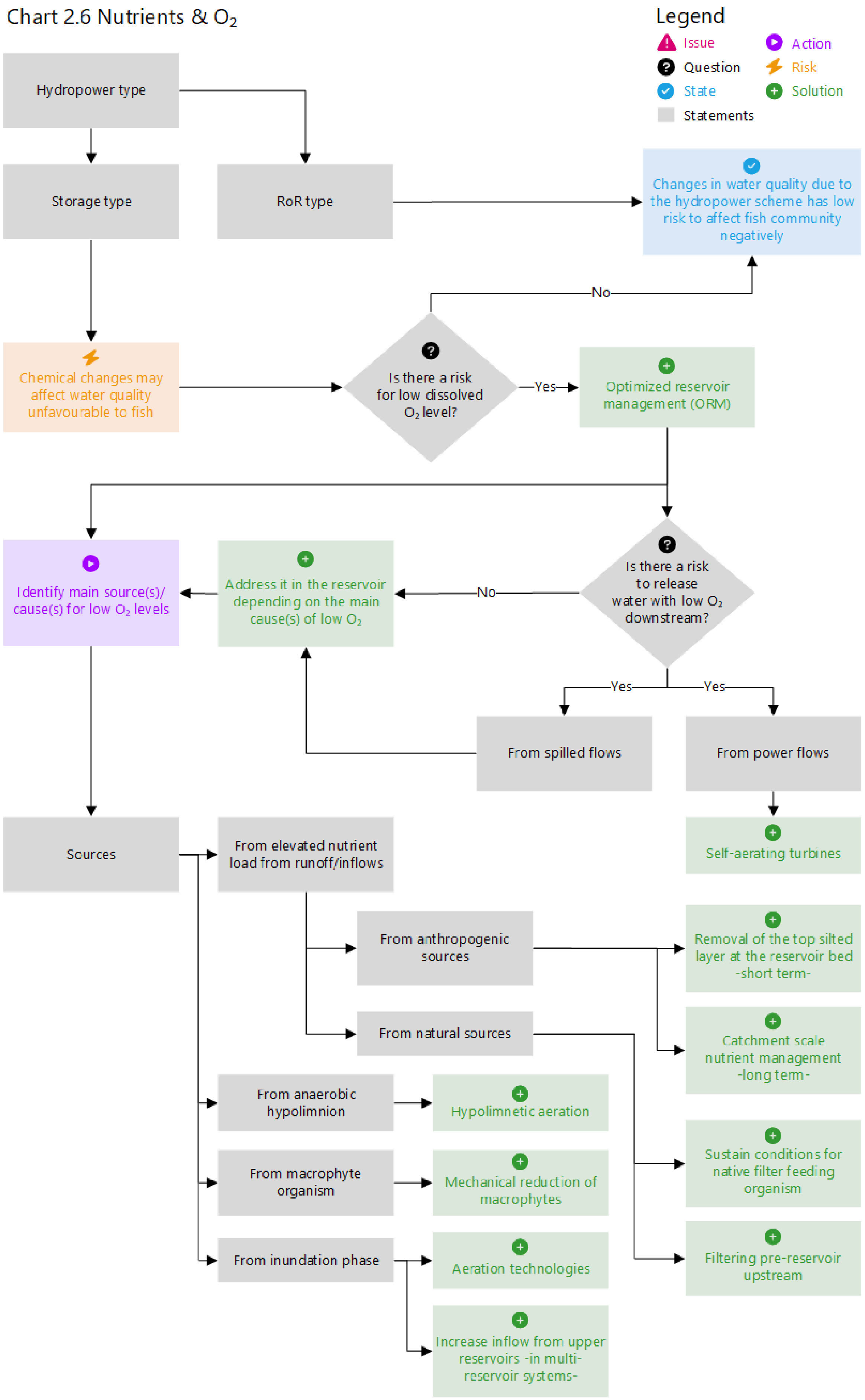


Chart 2.7 Supersaturation

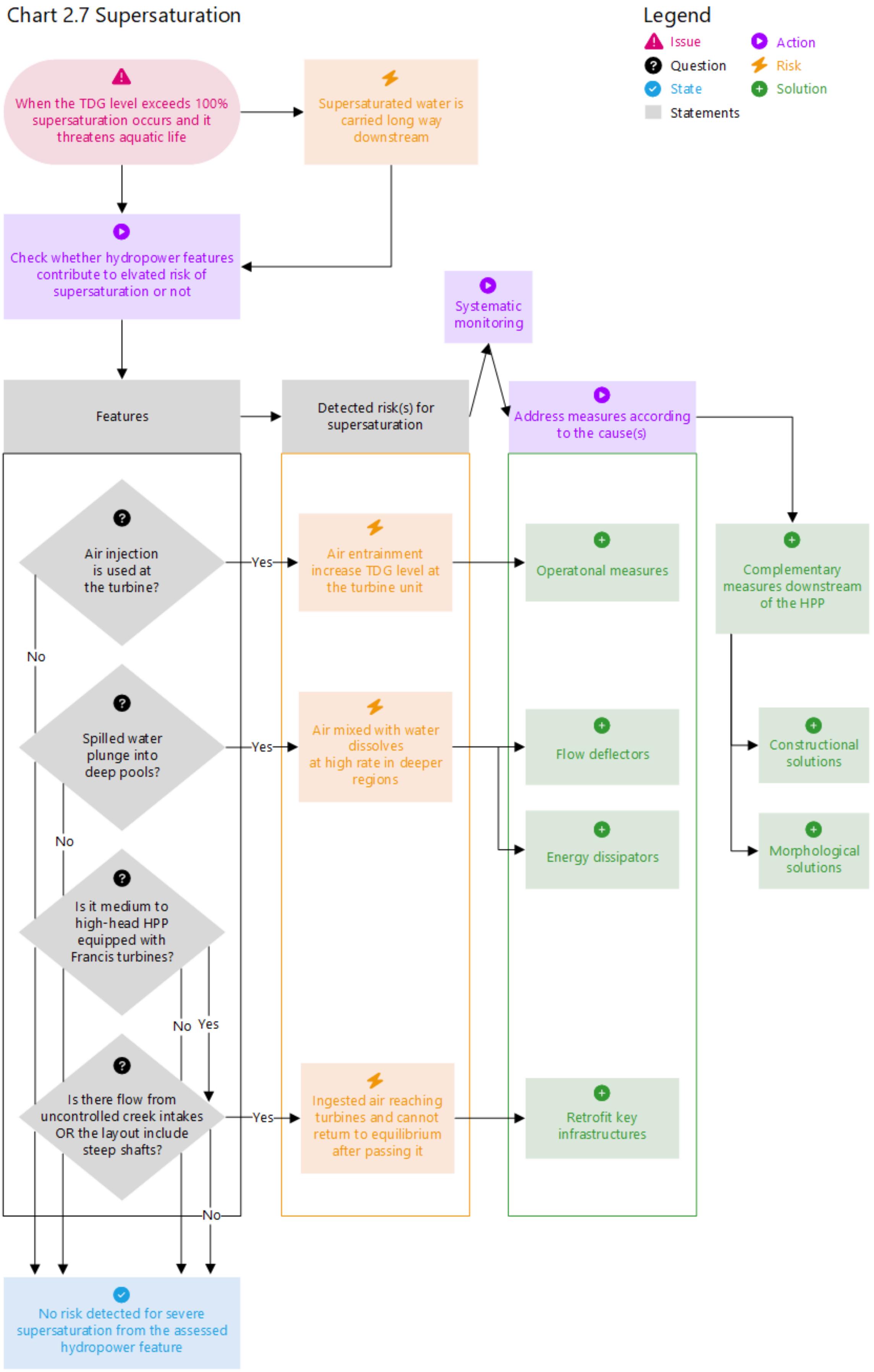
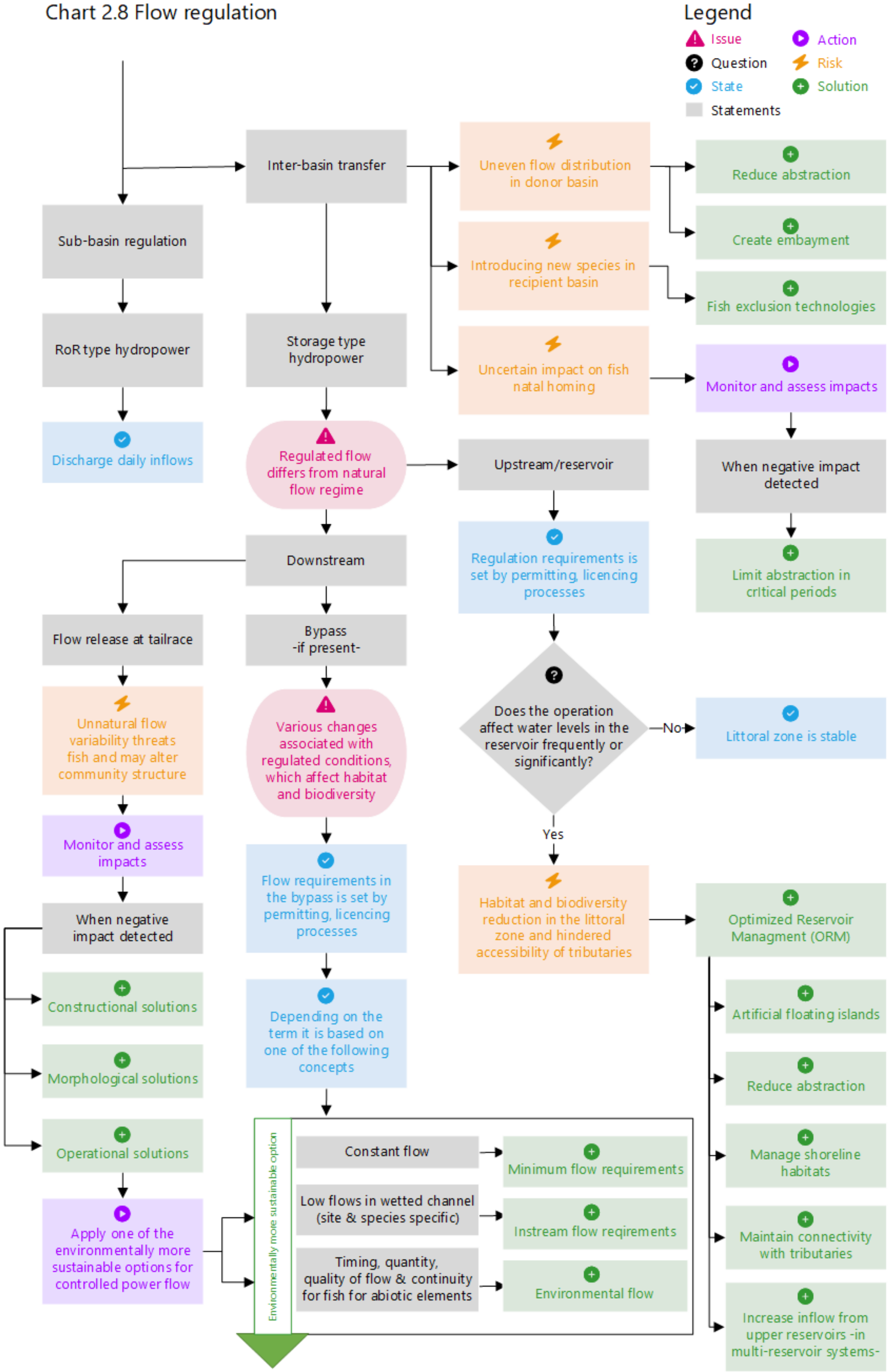


Chart 2.8 Flow regulation



SECTION 6: MONITORING THE EFFECTIVENESS OF SOLUTIONS

Section 6 presents monitoring techniques and other methods to assess the effectiveness of solutions or to characterize the abiotic and even biotic conditions in some cases, as the basis for **adaptive management of measures**. There are two primary reasons for such activities:

1. At the early stages of the investigation, assess the design aspects and suitability of proposed approaches (relevance).
2. After completing the works, optimize the implemented measure through a critical feedback loop (adaptive management of measures).

While the purpose of the monitoring may be different, but in many cases, the monitoring procedures will be similar. Monitoring during the design stage is typically used to evaluate the expected performance of various design features and options. The purpose of monitoring is to assess the effectiveness of the performance of the selected approach and preferably relate this to predefined objectives (e.g., a good ecological condition in line with WFD). It includes the following:

- Confirm that the operation of the as-built infrastructure meets all legislated requirements and provides optimal benefits for both the hydropower infrastructure and the fish communities.
- Providing input to the operation and maintenance program of the hydropower development.
- Providing crucial information on lessons learned and the feedback loop for continuous improvement.

At the end of the section numerical tools are presented for monitoring and design. The modelling techniques cover hydraulic and alternative models that can assess the various challenges for fish in hydropower-regulated watercourses. These include one-, two-, and three-dimensional modelling tools, habitat evaluation models, and statistical population models. Each functionality is explained, providing insights into its applicability for various scenarios.

6.1 Monitoring and Assessment Programs for Fish Passage

This section covers monitoring the effect and functionality of single mitigation measures, like fish passage efficiency and spawning habitat use, as well as effects on the population level of targeted species.

After new turbines or fish passage facilities are installed or rehabilitated, regulatory agencies and industry typically require a science-based assessment of claims for improvements in fish passage conditions. The assessment starts with developing field-testable hypotheses, proceeds through experimental designs, execution of field studies, and data acquisition, and concludes with hypothesis testing and other data analysis. There have been innovations across a broad range of technologies for fish passage monitoring and evaluations over the past two decades, including advancements in computing, physical models, sensors, experimental designs, risk assessment, mitigation strategies, and many other areas of science and engineering. Several relevant technologies are briefly discussed in this section.

However, the prime purpose of this section is to inform the reader about the various techniques used to monitor fish passage.

6.1.1 MODELLING FISH PASSAGE THROUGH TURBINES

Physical hydraulic modelling has been in widespread use since the 1940s. Performance models are based on Reynold's similitude for the prototype-model relationship. The hydropower industry typically uses them to evaluate the performance of hydraulic structures concerning power generation and cavitation. During the last two decades, observational physical turbine models (often referred to as observational models because of the Plexiglas construction) have often been used to evaluate fish passage conditions and the performance of turbines and other hydraulic structures [6.1]. Their prototype-model relationship is based on Froude's similitude, typically used for free-surface flows.

Numerical modelling has become a powerful tool for the biological performance evaluation of hydropower dams as high-speed supercomputers are more affordable and available. Many commercial CFD software packages apply to dams and hydro turbines. Other tools utilizing numerical simulations have also been developed specifically for fish passage. For example, the Biological Performance Assessment (BioPA) toolset relates CFD models of hydraulic conditions to known impacts on fish [6.2]. BioPA provides a relative risk analysis for fish passage by evaluating hydropower turbine designs and operations based on several injury mechanisms to fish, including rapid decompression, hydraulic shear, strike, and turbulence. Additionally, using numerical modelling of hydrodynamics to characterize the flow conditions at selected scales, from flows in different fish passage configurations to habitat distribution over tens of kilometres on a river. For more information on alike applications, see Section 6.4.

Blade-strike modelling is a cost-effective approach for turbine passage evaluation. It assumes that the blade will strike a fish if it does not pass within the sweeps of two adjacent blades. Von Raben proposed the first deterministic model for predicting the strike probability in 1957. Other researchers expanded the model and investigated fish passage through turbine runners and associated injuries. Two numerical blade-strike models depend on the assumptions for the input parameters: deterministic and stochastic models. The deterministic model assumes that fish are rigid bodies oriented perpendicular to the blade's leading edge and predicts a unique estimate for each combination of input values. The stochastic model analysis is usually performed using multiple realizations by assigning the distribution of the input parameters of possible values [6.3]. The stochastic model between these two models will usually better agree with experimental results and provide a more realistic prediction for blade strike rate and injuries because it incorporates how fish approach the leading edges of turbine blades.

6.1.2 HYDRO-ACOUSTICS TECHNOLOGY

The traditional hydro-acoustic technology detects fish moving through river reaches with acoustic sampling devices with transducers fixed in position. In the past three decades, this technology has been extensively used at hydroelectric facilities to study the approach and passage behaviour of both upstream-migrating and downstream-migrating fish [6.4]. Once the hydro-acoustic system has been calibrated, it has a high-resolution sampling capability over time and space. It can provide essential passage data, including route-specific passage rates, efficiencies, and horizontal and daily distributions. The significant advantage of this technology is that it is non-obtrusive, as fish collection or handling is not needed. The major disadvantage is that the system cannot identify species in most environments where several species are present.

Advanced imaging sonar technology bridges the gap between traditional fisheries sonars and optical systems. It has efficiently monitored fish passage in most turbid and dark environments [6.5]. Conventional sonars characterize acoustic targets but cannot capture images; conventional optical systems require light and clear water. The imaging sonars commercially available today have high resolutions and fast frame rates for potentially studying the correlation between fish behaviour and water flow. The existing disadvantages of imaging sonars are that they require intensive data processing due to the large amount of data collected during continuous surveillance and require a high capital investment.

6.1.3 BIOTELEMETRY

Biotelemetry allows users to remotely collect behaviour and movement information about fish in natural settings, such as riverine and marine environments. It has been used extensively for fish passage evaluation and monitoring worldwide. There are three leading biotelemetry technologies: passive telemetry, radio telemetry, and acoustic telemetry. Their tags can be internally implanted, gastrically inserted or externally attached.

Passive tags (such as passive integrated transponder [PIT] tags) contain no internal battery. They are only activated in the presence of an electromagnetic field when they pass close to an antenna. With billions of codes available, PIT technology is suitable for the long-term monitoring of many fish. It has widespread use worldwide. In addition, the size of PIT tags allows them to be injected into the coelom of the fish instead of surgical implantation. The main disadvantages of PIT tags are short detection ranges (typically a few centimetres to 1 meter, depending on antenna sensitivity) and low detectability outside a confined space. Therefore, the sample size required for fish passage studies is usually much larger than radio and acoustic telemetry. In addition, it is challenging to install PIT antennas on many passage routes, such as through turbines or spillways. Finally, PIT tags are ineffective for investigating the overall passage behaviour of fish passing through large hydroelectric facilities because it is challenging to detect PIT tags within a tailrace or forebay of the dam.

Example: PIT systems are deployed at most adult fish passes and juvenile bypass systems in the Columbia River Basin to identify individuals passing through specific routes [6.6].

Radio telemetry is an effective mobile tool for studying aquatic organisms in shallow freshwater environments [6.7]. For decades, it has been used to monitor the passage routes and subsequent survival of fish passing through hydroelectric facilities. While radio telemetry cannot track fish accurately in 3D, users can still derive passage routes of fish and estimate route-specific survival by deploying directional antenna arrays across the face of the dams and other locations upstream and downstream of the dams. Radio telemetry has a much larger detection range than PIT technology. Still, the signals from radio transmitters typically cannot penetrate through 10 metres of freshwater. Although radio transmitters can be implanted into a body cavity of the fish, they possess an antenna that is generally exterior to the fish to transmit the signal. In addition, the external antenna could become entangled, possibly reducing fish swimming performance and increasing fish susceptibility to diseases and infection.

Acoustic telemetry plays an increasingly important role in fish passage monitoring. It employs acoustic transmitters and receiving systems to track fish remotely in one, two, or three dimensions with sub-meter accuracy [6.8]. Acoustic telemetry has several advantages over the radio and passive telemetry technologies. For example, acoustic telemetry typically has long detection ranges in hundreds of meters, good performance in deep water, and the capability of determining three-dimensional positions with high accuracy and temporal resolution. This leads to the route-specific and complex behaviour of migrating fish in the proximity of and away from hydraulic structures. The acoustic transmitters are relatively expensive, but the technology is more affordable because new transmitters can be injected using needles instead of surgical implantation [6.9], leading to significantly reduced labour costs. In addition, the combination of tiny acoustic transmitters and the implantation of the transmitters by injection opens up the possibility of using acoustic telemetry to study fish species or age groups that were previously too small or too fragile to tag using larger transmitters or surgical implantation methods.

6.1.4 DIRECT BIOLOGICAL TESTING

Direct biological testing, such as the balloon-tag recapture technique and simulated turbine passage can improve our understanding of the physical passage parameters of fish. It is important to note that ethical concerns often arise with different kinds of laboratory fish tests.

The balloon-tag recapture technique permits the recovery of live fish by tagging them with self-inflating balloons after passage to observe their physical conditions [6.10]. It has been applied extensively for evaluating the direct injury and mortality rate of passage. While this technology has provided critical information on fish passing many hydraulic structures, one limitation is that it does not permit assessment of the response of depth-acclimated fish to the rapid pressure drop in the turbine because the study fish are acclimated to surface pressure before release. Because the study fish are not acclimated to the same depth as natural fish, the injury rates from the rapid decompression may not be accurately captured.

Laboratory testing using simulated conditions such as pressure, shear, or strike has provided new insights into fish behaviour. Injuries due to physical stressors such as rapid pressure decompression, blade strike, hydraulic shear, and the turbulence fish might experience when they pass through turbines or other hydraulic structures. Because of the difficulty in isolating the sources of injuries and controlling the physical stressors in field experiments, over the last two decades, much effort has been directed towards establishing precise and accurate laboratory equipment which can replicate the pressure profiles, strike, collision, shear, and turbulence experienced by fish passing turbines and other hydraulic structures. Laboratory studies link the observed biological responses to specific hydraulic conditions and stressors that are quantifiable and repeatable.

Example: The Mobile Aquatic Barotrauma Laboratory (MABL) is equipped with four hyper/hypobaric chambers used to simulate rapid decompression that occurs as fish pass through turbines at hydropower dams. MABL has been used extensively to better understand the mechanisms of injury and mortality related to barotrauma for many fish from North America, South America, and Southeast Asia. [6.11]

6.1.5 ENVIRONMENTAL DNA

Environmental DNA (eDNA) offers new opportunities to monitor species diversity in a given ecosystem. All living organisms leave fragments of DNA traces in their environment, these can be collected and analysed to determine a species occurrence or population status at the sampling time. Environmental DNA allows detecting of red-list species, monitoring invasive species' spread, or collecting information on the general distribution of species groups, like fish, invertebrates, or mammals [6.12][6.13]. When genetic markers of specific species are identified, more precise information can be obtained from eDNA studies. In addition, the samples can be stored for a long time, which gives a historical reference for biodiversity at the sampling time concerning any future changes from climate shifts or other impacts.

6.1.6 DIRECT PHYSICAL MEASUREMENTS

Live fish studies using biotelemetry and balloon-tag recapture techniques help understand the physical effects on fish of overall passage. Still, they cannot provide information on the physical conditions to which fish are exposed when they pass through the turbines or over spillways. In addition, it is essential to identify the locations and dam operations where physical conditions are severe enough to injure or kill fish. Therefore, direct physical measurements linked to specific fish responses can provide critical information for design criteria and the operation of fish passage facilities. For example, the artificial fish model, like the Sensor Fish[3] or the Barotrauma detection system (BDS)[3] devices are a small, neutrally buoyant autonomous package of sensors that characterizes the physical conditions and physical stressors to which fish are exposed as they pass through different kind of hydraulic structures [6.14]. The path during their passage through hydropower facilities can be divided into different regions by observing distinct features in the time histories of the data. This allows for the identification and classification of notable events that cause severe physical stressors and the location where these events occur. The field data can be linked to biological response models through an assigned software package for downstream fish passage at hydropower facilities [6.15]. The information provided by data analyses can then help hydropower operators and designers identify risks and physical stressors that may impact fish and develop alternatives that improve biological performance.

6.1.7 VIDEO SURVEILLANCE

Underwater cameras are commonly applied to monitor fish activities inside and nearby fish passage facilities. Several types and associated systems have been developed over the past decades to improve their performance. Conventional setups are limited to turbidity and light conditions. At the same time, modern systems combine them with infrared illumination to detect fish movement in the observed volume with fewer uncertainties.

Video surveillance also provides information to assess the population status of different fish species. In recent years, deep-learning techniques are emerging that filter video recording to detect species automatically while also registering the basic biometrics of individuals.

6.1.8 RESEARCH REQUIREMENTS

Knowledge gaps and uncertainties around the need and potential for installing fish passage facilities have been identified, and suggestions have been made to address these issues.

The knowledge gaps and uncertainties relating to fish species in regulated environments include the following:

- Baseline information on the fish species affected at each proposed hydropower plant during migration and movement. Such knowledge is obtained through field programs, monitoring, and laboratory testing or research. It is particularly important in regions and sites, where fish monitoring programs are less developed.
- Baseline information on the movement and migration cycles of the fish species affected at each proposed hydropower plant was obtained through field programs and monitoring.
- Understanding the potential impacts on these fish species due to passing through dedicated fish passage facilities or ecologically improved turbines obtained through laboratory testing/research.

The key to selecting fish passage options at hydropower plants is to prove their performance regarding survivability rates for the individual migratory fish species.

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[3] Disclaimer: links to the commercial developers are provided as the authors believe they represent promising technology, while only a few providers exist in the world to the author's knowledge.

Fish passage through the turbine units is not considered best practice on a general basis, but only as a complimentary measure to allow two-way migration over the barrier, as stated in Section 4.2.5. More specific research is necessary where ecologically improved turbines are used as passage technology. In terms of research, including the barotrauma effect of the turbines, the main areas to study cover:

- Applications of direct physical measurement technology at already existing dams, to characterize turbine passage conditions.
- Laboratory studies investigating the influence of turbine passage conditions on fish. This includes examining damage such as rapid pressure decompression, strike, and hydraulic shear forces from:
    - Fish ecology and behaviour.
    - When passing through the turbines, fish are exposed to sudden pressure changes.
    - The rate of injury and mortality and the range and rate of exposure to blade strike, collision, shear, and turbulence for different species.
- CFD and hydraulic modelling to improve turbine and water passage design.

In general, measuring the turbine-passage survival of every fish species in every hydroelectric turbine design is not feasible. To support the research activities, two analytical approaches should be considered:

- Research relating to the traits and physiology of fish to the conditions they could be exposed during turbine passage. An example of this is the Traits Based Assessment process.
- The use of models that include input from several sources. An example of this is the BioPA Tool.

6.1.9 SUMMARY AND APPLICABILITY

There have been significant advances in monitoring and evaluation technologies to assist the development of environmentally friendly hydraulic structures, optimize routine operations for efficient power generation, and mitigate fish passage issues. Regulators can then validate the operator's dam performance claims, leading to improvements to fish passage conditions and downstream water quality. This process integrates physics, engineering, and fish biology. It requires multiple technologies, including direct physical measurements, controlled laboratory studies, and field trials. In addition, collaboration and information sharing within the hydropower and fish passage community are critical due to the complexity and typically limited funding for research, monitoring, and evaluation of fish passage facilities.

Section 6.1 covered the technology and methodology for monitoring and assessing performance. This section will guide the reader to determine and design the appropriate monitoring approach or series of approaches for different purposes. An overview is given in Table 6.1.

Table 6.1 ***Applicability of monitoring techniques***

MONITORING TYPE	DESCRIPTION-PURPOSE	PASSAGE LOCATION	LIMITATIONS	COMMENTS
Modelling - physical	- General evaluation of fish passage conditions and performance.	- All, including fish ladders.	- Need to address scaling effect. - It provides only relative fish injury comparison.	- Mature methodology as it has been used for many years.
Modelling - numerical	- Powerful simulation tool for biological performance.	- All, specifically turbine and fishway passage.	- Can only provide relative fish injury comparison.	- Applications are evolving.
Hydro-acoustic Technology	- Detects fish movement through fixed transducers.	- Passage behaviour for both upstream & and downstream movement.	- Difficult to identify species.	
Biotelemetry	- Biotelemetry types are passive, radio, and acoustic telemetry.	- All structures.	- Tags surgically injected, implanted or externally attached.	
Direct biological testing	- Balloon-tag recapture technique, and laboratory simulation testing	- Downstream passage.	- Balloon-tag recaptures do not measure barotrauma.	
Environmental DNA	- By water samples collecting DNA fragments from individual species and species groups.	- Any river section (macro-scale).	- Provides information about biodiversity (species & groups).	- For specific species identified genetic markers are needed. - Useful for studies on fish abundance.
Direct Physical measurement	- Small, neutrally buoyant autonomous devices with sensors characterizing physical conditions and stressors.	- Downstream passage.	- Can only provide relative fish injury comparison.	- Linkage to biological response models developed using direct biological testing.
Video surveillance	- Observing fish activities nearby fish passage facilities with underwater cameras.	- Nearby and inside of fish passage facilities.	- Limited use in turbid and dark conditions.	- Can be combined with deep-learning techniques to register fish species and movement automatically.

6.2 Monitoring and Assessment of Mitigation Measures Addressing Fish Habitats

Monitoring techniques for assessing fish passage efficiency are presented in Section 6.1. Several of the same techniques are also relevant for studies of habitat use by tagged fish (e.g., radio tags or PIT tags). Some are also relevant for evaluating other implemented measures mitigating various negative impacts of hydropower on fish. Techniques like biotelemetry or eDNA provide sufficient information to support the adequate implementation of such measures, like environmental flow release, to preserve or restore fish habitats. Several methodologies have been developed to monitor and assess the efficiency of hydropower mitigation measures directly. The current section describes their functionality to evaluate environmental flow measures, sediment management and hydropeaking mitigations.

6.2.1 BIOLOGICAL SAMPLING

In Rivers

Electrofishing has been one of the most applied methods for assessing the fish populations in rivers. Traditionally, it has been based on personal wading in shallow river sites with hand-held equipment to encounter and immobilize fish for registering their biometrics. Several guidelines and international standards are available, which describe limitations and conditions for the suitable use of electrofishing [6.16][6.17]. Recently, boat electrofishing has become a common alternative to use to a larger extent (at non-wadable river sites). It is also possible to elevate the precision of the technique by using some markings on fish to eliminate the registration of recaptured individuals. The outcome is normally expressed as fish abundance per river area (for a wading session) or fish biomass per river km (for a boat session), divided into year or size classes of relevant species.

Seasonally installed traps are used for migratory fish species to monitor fish populations during migration seasons. There are different types of traps, like a screw, wheel-type, and net-based (fyke) solutions are commonly suitable for fish monitoring. They require frequent check-ups and fish unloading to minimize delays in their migration and not threaten their survival.

In Reservoirs and Ponded Sites

Multi-mesh gillnet fishing has historically been widely used to monitor fish populations in large ponds and reservoirs [6.18]. Recently, echo-sounding techniques are emerging to assess the abundance and habitat use in limnic sites.

6.2.2 HABITAT USE ASSESSMENT

Habitat monitoring aims to collect information on characteristics like habitat types, abundance, size, variability, and hydro-morphological conditions. Hydro-acoustic (Section 6.1.2) and biotelemetry techniques (Section 6.1.3) can collect some information indirectly through fish monitoring, while other techniques record data from the abiotic environment. Generally, assessment of substrate conditions and sediment transport is essential for habitat evaluation and improvement in regulated watercourses [6.19]. There are plenty of Many sediment sampling and analysis techniques are available, either in-situ or ex-situ. For detailed information, the reader has advised the check the available literature [6.20][6.21][6.22].

Additional techniques like diving or underwater camera observations are commonly used for addressing habitat abundance. In contrast, advanced techniques like Acoustic Doppler Velocimetry are suitable for collecting hydraulic data for flow condition assessment. More techniques and information are found in the literature [6.23]. Some measurements shall be repeated to cover the seasonal aspect at given sites for fish species (Figure 6.1)[6.24]. All the collected information provides a sufficient basis to assess habitats in their current form or even to design and evaluate environmental flow releases. Also, the collected data serve as input for further habitat analysis in a combination of testing mitigation measures via numerical techniques, as presented in Section 6.4.

Figure 6.1 ***Winter habitat use of pit-tagged fish by use of portable PIT-tag antenna in a tributary of River Gaula in Norway*** (Source: Jo H. Halleraker, [6.24])

6.2.3 IMPORTANCE TO LINK HYDRO-MORPHOLOGICAL CONDITIONS AND FISH

Hydropower development alters the hydro-morphological characteristics of regulated watercourses. Knowledge of the relations between fish and substrate provides a sufficient basis for mitigation measures addressing the altered conditions.

One of the main concerns with hydropower regulation in this context is the impact of hydropeaking on the aquatic environment. Stranding and flushing of smaller aquatic animals have been studied over the past few decades concerning the flexible operation of hydropower. The studies revealed that smaller individuals, like juvenile fish, are more vulnerable to rapid and frequent flow ramping. The survival (or escape) rate of smaller aquatic animals during such hydropower operation depends on factors like light, water temperature, life stage, and habitat (substrate) characteristics. The linkage between biota and the environment can serve as a design basis for adjusting operations or other solutions for hydropeaking impact on fish. In combination with installed water-level sensors in the tailrace and further downstream, it becomes a cost-effective tool for applying and evaluating mitigation measures for hydropeaking [6.25].

Another concern with hydropower regards sediment continuity and substrate degradation in the watercourse. Many fish species depend on adequate substrate composition during their different life stages for spawning, feeding or using it as a shelter. The links between fish preferences and substrate conditions can be established from habitat assessment via sampling and monitoring (Section 6.2.2). Such relations are then essential for the numerical assessment of sediment conditions in the regulated river sites and jointly for habitat evaluation models using techniques presented in Section 6.4.

6.2.4 STANDARDS FOR STATUS CLASSIFICATION OF FISH ECOLOGY

A classification system must relate the collected data on fish and their habitats to a management context. It also functions as a standardized tool to evaluate relevant hydropower mitigation measures. The acquired knowledge of ecology must be related to either of the following cases:

A. A reference condition (preferably pre-impact state or reference site with non-impacted ecological status, for instance as used for defining good ecological status described in the WFD).

B. To another determined environmental objective (i.e., best available mitigation techniques or ecological potential, as described in the WFD).

One or both cases are already established in many countries and jointly implemented in the European Water Framework Directive. Several European guidelines on river monitoring classification and mitigation library are available in alignment with the two cases above. Other countries have used intercalibrated classification systems for sustainable river management [6.26].

Example: One classification system is the Austrian Fish Index, that has been described and tested in a number of regulated rivers with various level of hydropeaking intensity and the interaction with the habitat conditions in Austria. The results showed that habitat conditions, peak frequency (number of peaks per year), ramping rate (water level variation) and interaction between habitat and ramping rate explained most of the variation in the degraded fish communities. The results show that fish stranding caused by ramping rates larger than 15cm/h are likely to be the main cause of fish community degradation when occurring more often than 20 times a year. The fish index is based on electrofishing data from a representative part of the impacted rivers of Austria [6.27].

6.3 Water Temperature and Quality Monitoring

The construction and operation of dams can affect water quality in reservoirs from impoundments and downstream rivers in various ways, as discussed in Section 3.2.4 and addressed in Section 4.5. Direct effects include spatial and temporal changes in water temperature, DO, nutrients, turbidity, TDG, and more. Dam owners and operators may need to provide water quality measurements in the field during the permitting process and operations for compliance purposes.

Considerable effort has been devoted to addressing concerns about water quality, especially DO and the need for solutions to improve DO concentrations in water. Several technologies have been developed and applied at hydropower plants to meet DO compliance for improving DO concentrations downstream (see Section 4.5.2). These technologies have high capital costs and technologies like diffusers have high costs when used. Therefore, collecting detailed DO measurements at multiple locations is critical to develop accurate predictive models for deploying and operating DO-enhancing technologies for optimal performance. Even though the concept above is applicable to DO measurements, the monitoring approach for other water quality parameters commonly follows a similar approach.

Another water quality parameter affected by hydropower is the amount of TDG in the water column. Note, that TDG is not to be confused with DO levels. DO is often used mistakenly as a proxy for TDG assessments in watercourses. However, there is no linear relationship between DO and TDG levels in watercourses. As water passes over spillways, it entrains gases, leading to elevated levels of TDG in the water column. Typically, TDG levels in unregulated river systems are approximately 100%. However, TDG levels as high as 140% and beyond have been measured in rivers heavily impacted by hydropower.

Water temperature is also a key factor in aquatic ecosystems. Temperature loggers have become inexpensive and durable to deploy in several conditions like reservoirs, hydropower outlets, or bypass channels. Ice conditions are also relevant to monitor via remote sensing at winter habitats. The collected information serves as input data to numerical models (Section 6.4) to characterize current temperature conditions for fish.

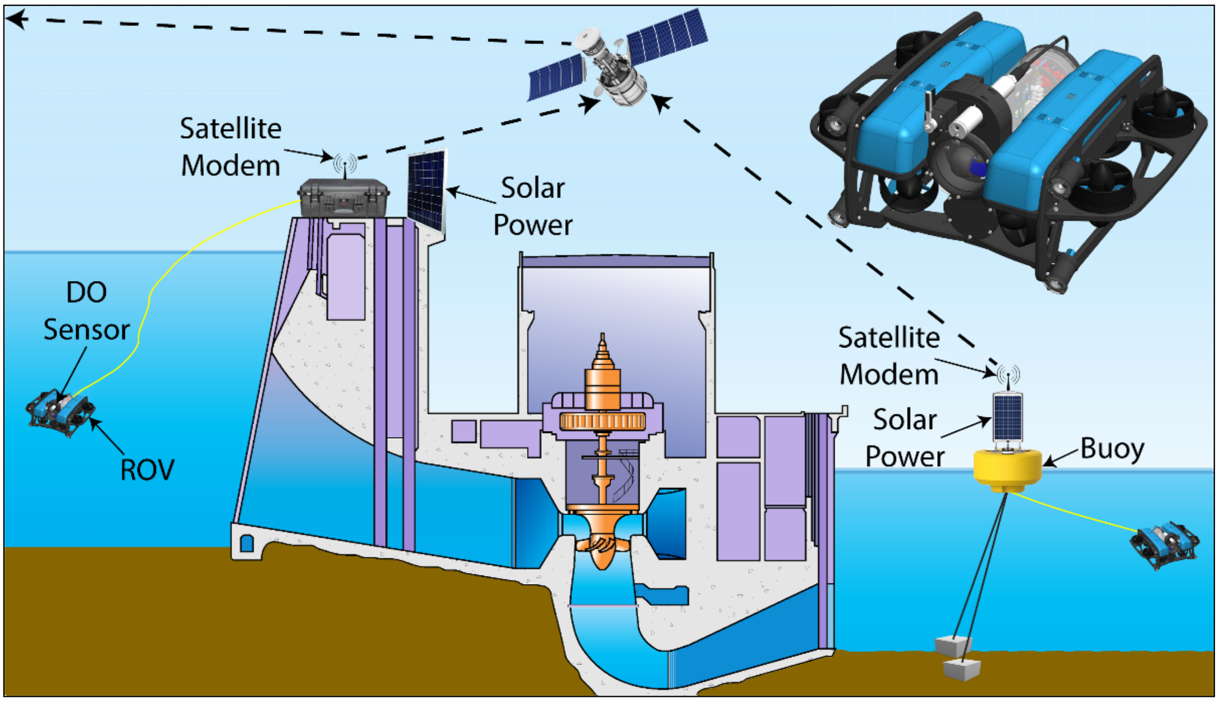

Figure 6.2 ***Visualization of a real-time and autonomous water quality monitoring system that utilizes a remotely-operated vehicle in operation*** (Source: [6.28])

To provide appropriate and effective data inputs for hydropower licensing and optimum operations, several key elements should be considered:

- **Accuracy and comprehensiveness of measurements.** Measurements must be taken at enough locations across a river section and through the water column to characterize the variation of monitored properties. Monitoring stations installed at fixed locations, either attached to an existing dam structure or on a buoy anchored to the river bottom, collect information with a fixed spatial baseline. However, it is also important to conduct predetermined measurement campaigns to allow sufficient temporal and spatial resolution.
- **Worker safety during data collection or equipment maintenance.** Water quality monitoring efforts are often contingent upon worker safety, particularly where fixed monitoring stations are not feasible. For example, some DO monitoring plans require sampling areas close to the turbine intake. Furthermore, fixed-location monitoring stations cannot be put in dam intakes and tailraces due to worker safety concerns. This inhibits the dam operator's capacity to collect data from a

rapid flow environment where DO mitigation systems are frequently installed (at intakes or tailraces) to evaluate their effectiveness at oxygen transfer.

- **Communication between monitoring stations and the dam operators.** Many water quality monitoring plans for hydropower projects require monthly sampling or retrieval of hourly logged data during equipment maintenance visits, which can be sufficient for compliance efforts. However, the real-time availability of water quality data allows the power-plant operator to observe the measurements in real time and operate mitigations equipment as needed, reducing the frequency of turning on and off the turbines.
- **Status monitoring of the sensor equipment.** Due to the possibility of biofouling, for sites that require high data accuracy, the sensor's maintenance may be required weekly or more often. Real-time sensor status monitoring can avoid unnecessary and costly technical site visits.

Some autonomous real-time water quality monitoring systems are available (Figure 6.2), such as the solutions provided by NexSens and Fondriest Environmental. They are installed at fixed locations on a river buoy, dam, or riverbank mounting structure. A recently developed system uses an autonomous mobile sensor platform utilizing an autonomous remotely-operated vehicle (ROV) that can operate in dangerous water environments near hydropower facilities (e.g., intake, tailrace) and a solar-powered mobile docking platform for powering the ROV [6.28]). It also includes a cloud-based software interface that enables remote access to real-time and historical sensor readings and status.

6.4 Modelling Tools for Fish and River habitats with Hydropower Impacts

A large number and variety of numerical tools are available to support eco-hydraulic projects. Several factors contribute to the selection of modelling approaches in a project. Depending on the subject of interest (e.g., water level variations downstream of the tailrace from hydropeaking, hydraulic conditions within fishways, the seasonal response of water temperature in reservoirs, among others), data abundancy and needs (i.e., sufficient temporal and spatial resolution, and also for model calibration and validation), available budget and time for the project the numerical tools vary from less complex 1D to highly advanced studies in 3D. There are adequate tools to analyse cases such as river continuity, habitat abundance, or sediment development in current or planned scenarios. In any case, the selected approach needs a topological mapping from the study area and recorded hydrological time-series data to set up the virtual domain of the area. Typical field mapping methods include echo sounding, total station or RTK GPS, or airborne laser scanning. Upon calibration and validation, numerical tools have become essential for analysing eco-hydraulic projects.

6.4.1 ONE-DIMENSIONAL MODEL

One-dimensional models are used to model river flow in long river stretches or to study the effects of short-term regulation in rivers with multiple power stations. The results can provide a set of averaged flow velocities, water levels, and depths based on the cross-sections of the river. These models can simulate the water level and flow velocity variations caused by hydropower use and microhabitat evaluation. Examples of water levels along a river and temporal water level variation caused by short-term hydropower regulation are shown in Figure 6.3. Commonly used software includes BASEMENT, HEC-RAS, and MIKE 11 examples.

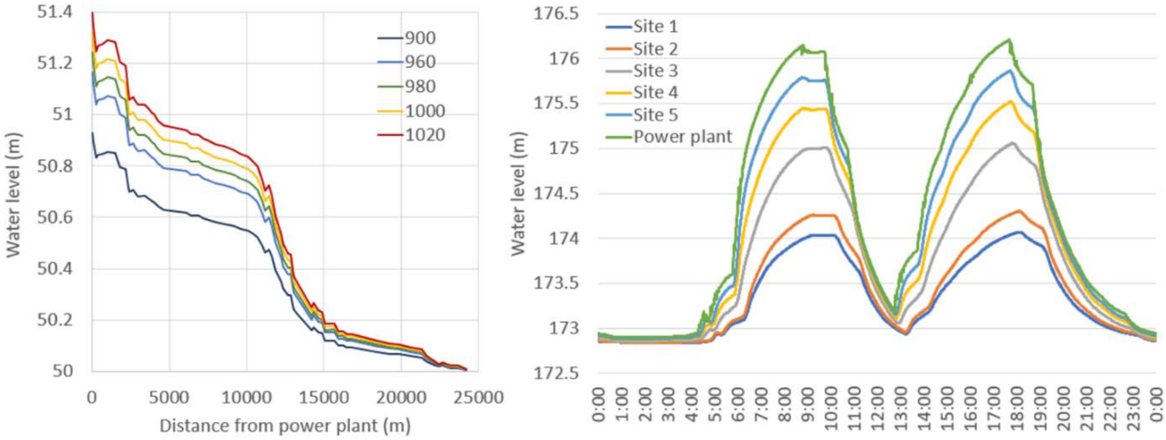

Figure 6.3 ***Water level downstream of a hydropower station along a river with different steady discharges (m^3/s) (left) and water level in a river immediately downstream of a power station and at five sites downstream during a short-term discharge regulation scheme studied (right).*** (Source: Markku Lahti)

6.4.2 Two-Dimensional Models

Two-dimensional models simplify the velocity field with depth-averaged flow velocities and simulate cases where vertical flow variation is not essential. The result is depth-averaged flow velocities, water levels, and depths in a horizontal grid.

The grids can be rectangular, but flexible meshes are most common nowadays, allowing adjustments to river geometry. Such tools have proven useful in detailed fish micro- and macro-habitat evaluations in relatively shallow rivers [6.29]. Most recently, even longer reaches and/or periods, as well as dynamic phenomena, can be modelled. Commonly used software includes AdH, BASEMENT, Flow2D, HEC-RAS 2D, MIKE 21, RIVER2D, and Telemac 2D. An example is shown in Figure 6.4.

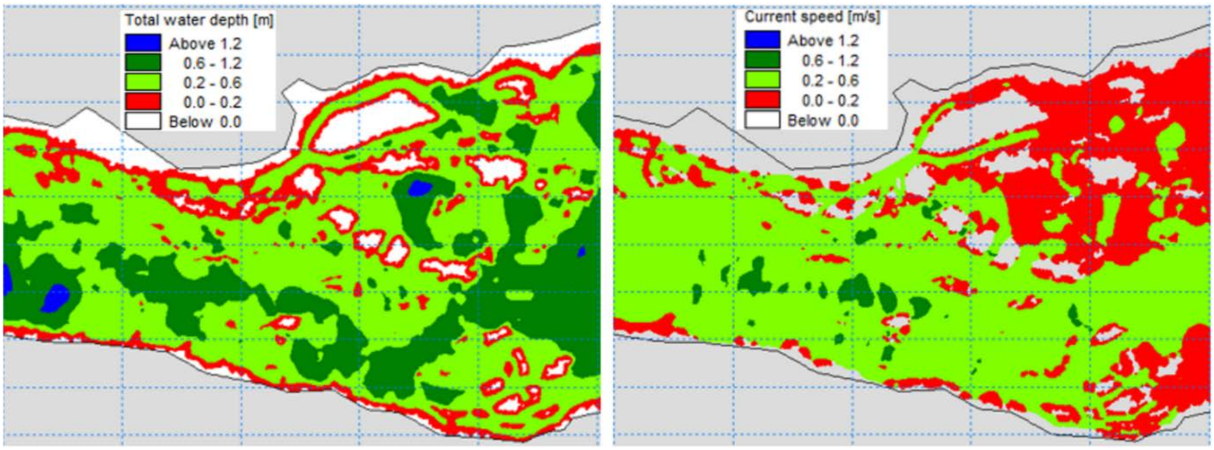

Figure 6.4 ***Water depth and flow velocity modelled with a two-dimensional hydraulic model under a flow rate of 15 m^3/s in the Rapid Stora Åråsforsen of the Gullspångsälven River in Sweden*** (Source:[6.30]).

6.4.3 THREE-DIMENSIONAL MODELS

Three-dimensional single- or two-phase (free surface) models are used to simulate three-dimensional flow adjacent to structures; in practice, many estimations close or adjacent to hydropower stations, dams, and gates can be carried out. Applications of 3D models also include planning channels adjacent to hydropower stations or evaluating flow in these. This can include studying upstream or downstream fish migration, evaluating fishway entrance design and location, and the effects of different attraction flows and structures for fish guidance. For upstream migration of fish, the most effective selection of turbines to connect with attraction flows from fishways or fish traps can be studied by modelling the hydraulics in tailraces. Hydraulics of fishways and bypasses and attraction flows can also be modelled. Commonly used software includes ANSYS (CFX and FLUENT), Delft 3D, Flow3D, OpenFoam, REEF3D, Star-CCM+, SSIIM, and Telemac 3D. Examples are shown in Figure 6.5.

Example: Effects of discharges and turbine selection in combination with attraction flow from a fish trap on tailrace hydraulics were studied in the Oulujoki River to optimize fish trap performance. Hydraulic modelling of the fishway mouth area at the Merikoski hydropower station is shown in Figure 6.5 [6.31].

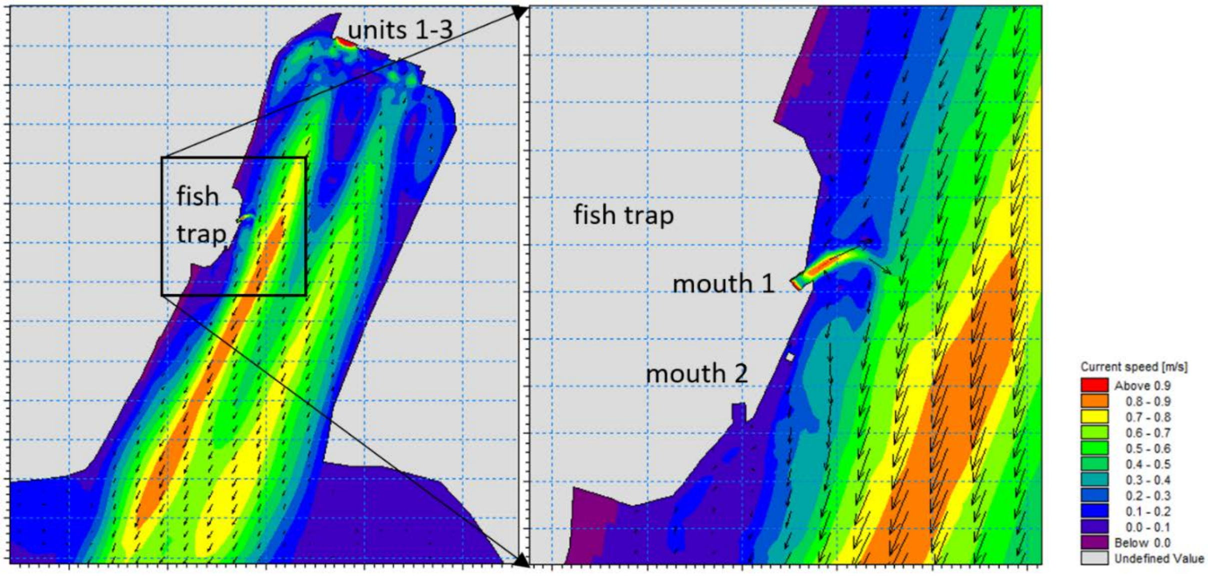

Figure 6.5 ***Flow velocity modelled with a three-dimensional hydraulic model in a tailrace of the Montta hydropower plant on the Oulujoki River in Finland to study the function of a fish trap and the effects of attraction flow and unit combinations on the flow situation affecting fish attraction to the trap*** (Source: [6.31]).

A general comparison of the three main hydrodynamic modelling techniques is presented in Table 6.2.

Table 6.2 ***Comparison of the functionality of hydrodynamic models***

		NUMBER OF MODELLED VELOCITY COMPONENTS	DATA REQUIREMENT AND COMPUTATIONAL EFFORT	SPATIAL AND TEMPORAL RANGE	MAIN BENEFITS OF THE DIFFERENT APPROACHES FOR ECO-HYDRAULIC PURPOSES
Modelled flow complexity	1D	One component	low	large	Simple tool to assess conditions before and after measures on larger extents (e.g., weir removals on 10+ km river site).
	2D	Two components	medium	medium	Computationally affordable tool for more detailed assessment of current or planned scenarios (e.g., for habitat suitability).
	3D	Three components	high	small	Highly advanced tool to characterize hydrodynamic properties in critical locations (e.g., flow conditions in fishways or turbines).

6.4.4 HABITAT EVALUATION MODELS

The most significant advantage of habitat models is to provide quantitative assessment results that strongly support decision-making processes. Habitat suitability approaches like PHABSIM, CASiMiR, and MesoHABSIM can provide high-confidence management recommendations by establishing quantitative relationships between flow river morphology and biological response. A particular strength of habitat models is that they consider channel alterations, which have a substantial limiting influence on habitat availability; however, they require extensive fieldwork by specialized scientists to acquire quantitative knowledge of the habitat preferences of aquatic biota across multiple life stages and variable flow levels (seasonally and inter-annually).

Still, with rapidly growing data acquisition and analytical technology, habitat models can be applied in the broader context of determining habitat needs for entire aquatic communities, including seasonal and life-stage variability.

Habitat modelling approaches determine requirements of target species at reach scales (from a few hundred to several km-s) in river systems and quantify flows supporting and providing these habitats for fish (and for aquatic insects, mussels, crustaceans, and plants). The main micro-habitat variables examined tend to be water depth, velocity, substrate (i.e., riverbed grain size), and cover (shading of riparian vegetation and shelter within the river from large woody debris, among others). Micro-habitat needs are also defined for different life stages and seasons [6.32][6.33]. For riparian plant species, sediment grain sizes and moisture regimes are important micro-habitat variables. Habitats are also commonly delineated at a mesoscale composed of river geomorphic units such as riffles, pools, and glides, among others [6.34]. Relationships between habitat variables and the abundance of target species may be simulated and expressed in habitat suitability criteria mapped in one, two, or three dimensions in stream and river reaches (Figure 6.6).

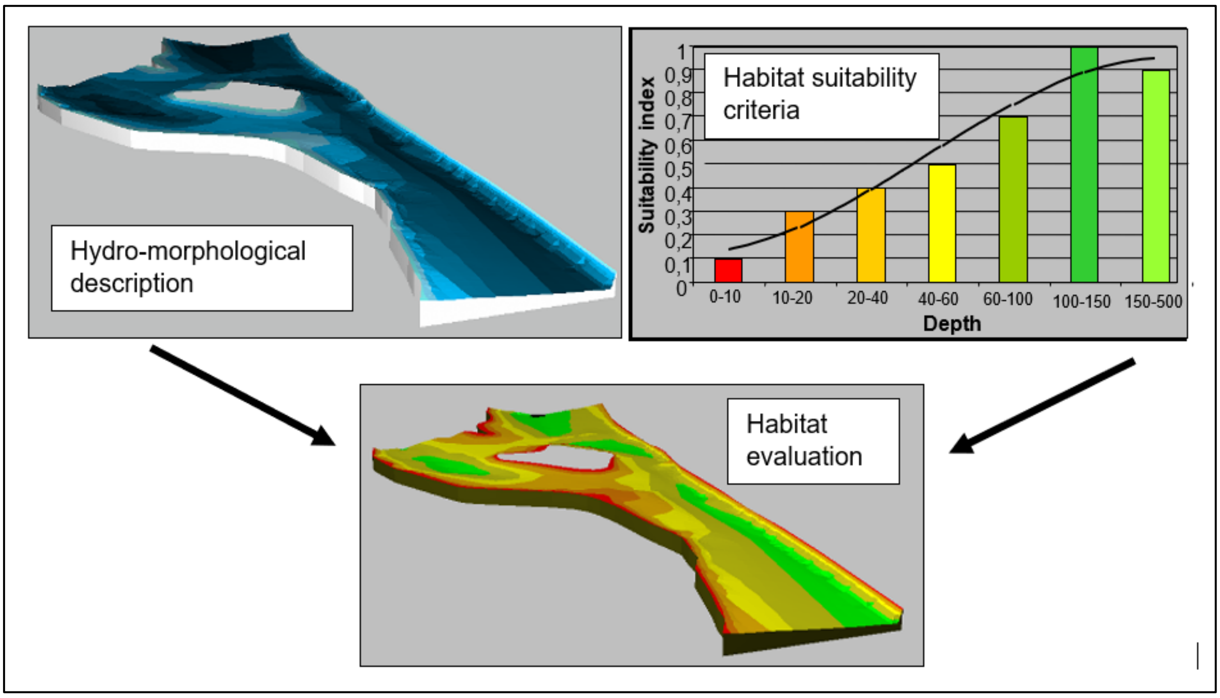

Figure 6.6 ***Illustration of habitat suitability criteria- combined with relevant variables*** (Source: [6.35])

The most applied software for micro-habitat suitability simulation is Physical Habitat Simulation (PHABSIM), developed in the USA as part of Instream Flow Incremental Methodology-IFIM [6.36]. Other models developed on similar lines include RHABSIM developed in the USA; RYHABSIM, developed in New Zealand; EVHA, developed in France; and RSS, developed in Norway [6.37]. Habitat assessment models like River-2D and CCHE-2D involve 2D hydrodynamic modelling to establish the flow and hydraulic parameter relationships. For mesoscale simulation of habitat suitability, models such as SIM-Stream software [6.38], Mesohabitat Evaluation Model [6.39], MesoCASiMiR [6.40], and the hierarchical framework developed within the REFORM project [6.41] are available. Applying each approach requires detailed knowledge of the habitat preferences of species living in the rivers under study.

Based on hydraulic models, so-called individual-based fish habitat models can be used. Fish behaviour, feeding, growth on the individual level, and interaction with other organisms are modelled on a temporal scale.

Advanced habitat time series analysis in the model allows the establishment of standard denominator metrics, such as Habitat Stress Days or Community Habitat Structure Alterations that can be used in quantitative scenario comparisons within a River Restoration Analysis framework [6.42]. As the model was created based on GIS, it is characterized by flexibility in the simulation of morphological changes, allowing set reference conditions and analysis of potential actions (such as channel improvements) to compensate for habitat shortages in the river. The final elements of the methodology are indexes and tools enabling the implementation of results in operational activities and comparison of planning scenarios that are particularly useful in adaptive management. An example is given in Figure 6.7.

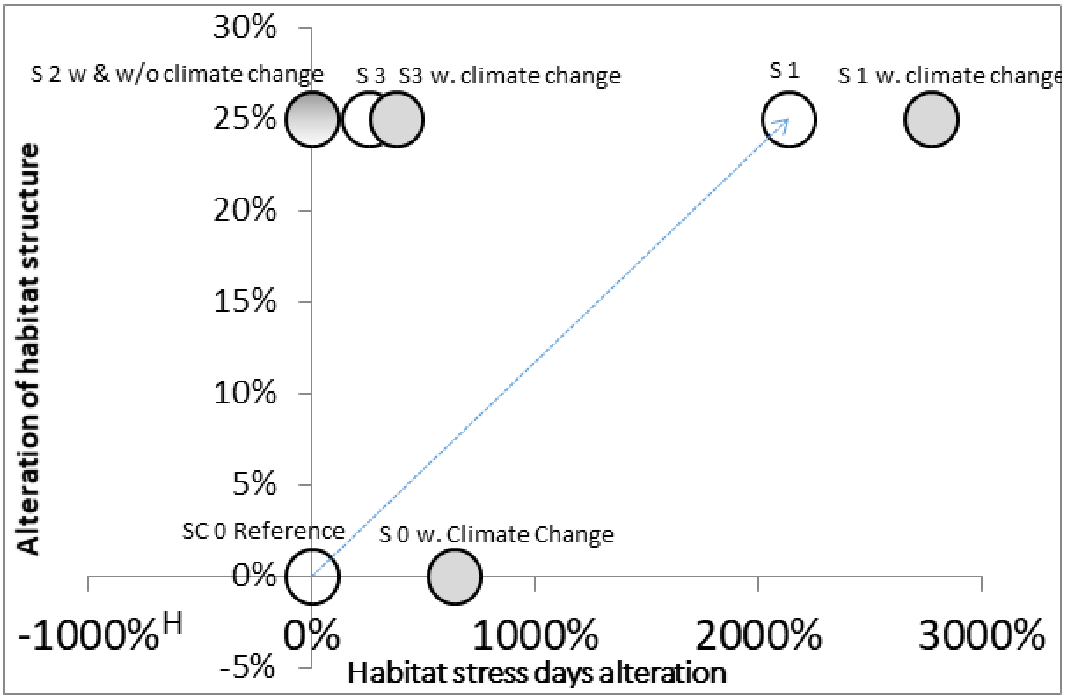

Figure 6.7 ***Restoration Alternatives Analysis for simulated scenarios for the Guadalhorce River in Spain with historical and future flow conditions. S0 represents reference conditions, S1 is the current situation, S2 is dynamic e-flows, and S3 is for static minimum flow scenario. Grey circles represent the above scenarios under simulated climate change*** (Source: [6.43]).

6.4.5 STATISTICAL POPULATION MODELS

In addition to models based on hydraulics, statistical population models are used to estimate the effects of different physical factors on the success of fish populations in a river with a hydropower plant. Commonly used parameters are flow rates, water levels or water temperature. In the latter example, the linkage between temperature and fish growth is well-known for several fish species [6.44]. In alike models, the entire life cycle of migratory fish can be considered from sea to upstream spawning areas and back. These models can identify the crucial parameters to focus upon, for example, in planning the management decisions for re-building fish stocks in regulated rivers.

Example: The important life-cycle parameter values for Baltic salmon (*Salmo salar*, evolved type from the Atlantic salmon) have been based on literature and the general life-history model used for their population modelling by the International Council for the Exploration of the Sea. When Baltic salmon population re-building trajectories were modelled for strongly regulated rivers of the Bay of Bothnia, several realizations of possible future scenarios were produced. Management decisions include regulating fishing mortality in offshore, coastal, estuarine, and river fisheries and managing environmental factors. These include assuring safe smolt passage at hydropower dams and favourable egg to smolt survival in the fluvial environment through habitat restoration in free-flowing stretches of the former naturally salmon-bearing rivers. The model indicated that these factors in freshwater life stages might also play an essential role in determining the realized trajectories in salmon population restoration [6.45][6.46].

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