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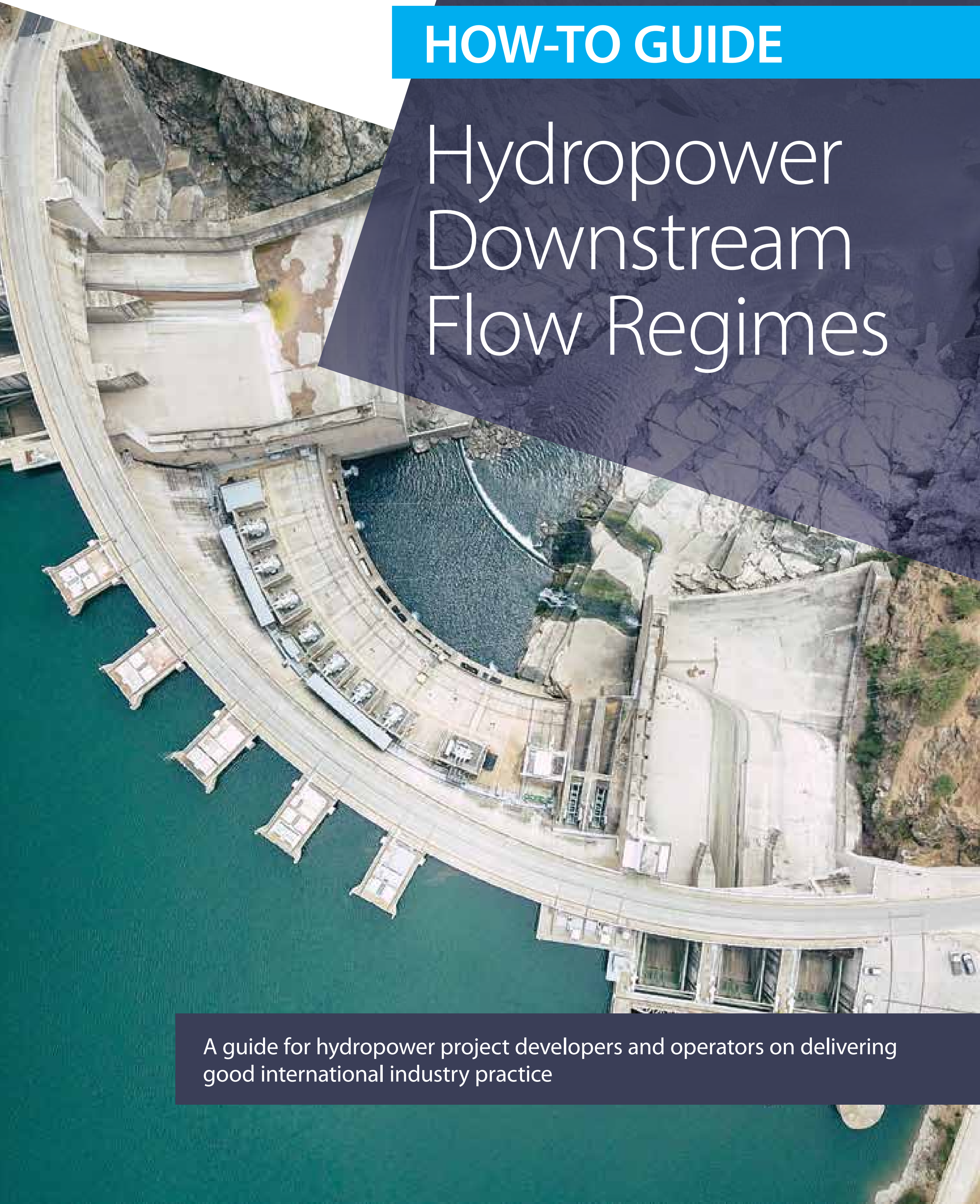
HOW-TO GUIDE

Hydropower Downstream Flow Regimes



A guide for hydropower project developers and operators on delivering good international industry practice

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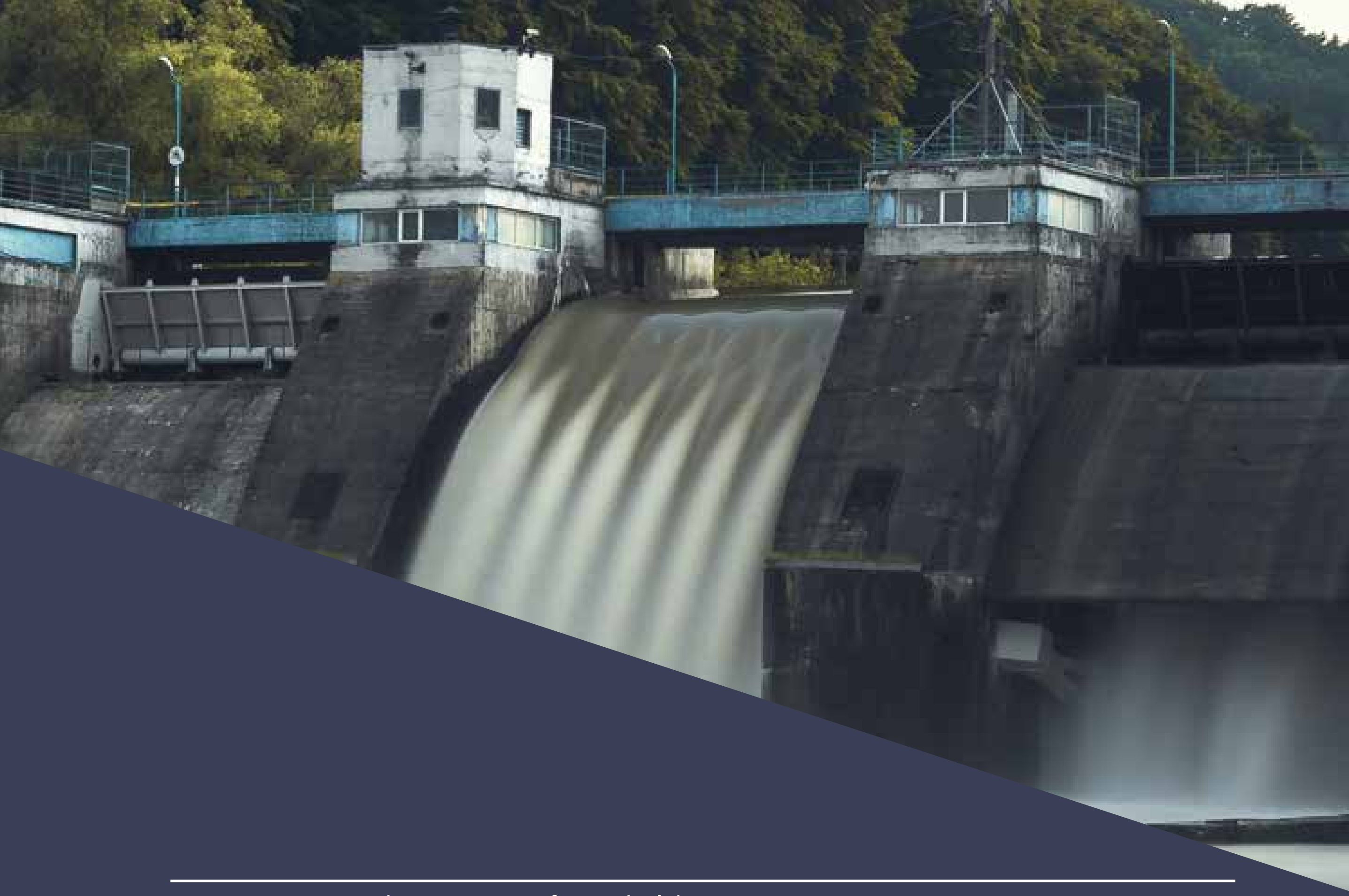


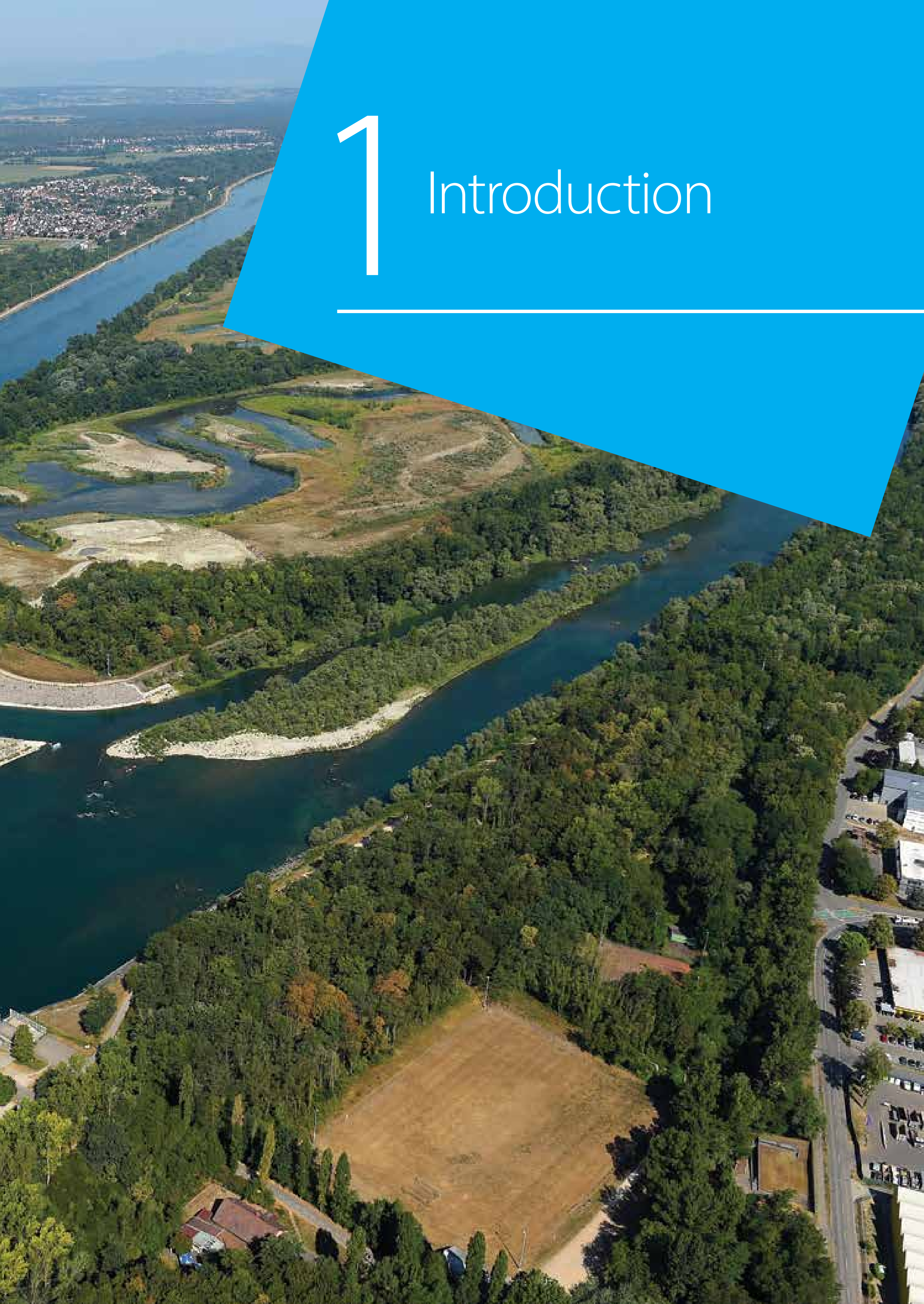
Glossary

The following is a selection of key terms. A highly comprehensive glossary of terms is available in the International Glossary of Hydrology, published by the World Meteorological Organsation (WMO) and the United Nations Educational, Scientific and Cultural Organization (UNESCO) in 2012.

Controlled flood release	The temporary release of a pulse of water to mimic natural flood conditions; can also be called 'pulse flow' or 'flushing flow'.
Degree of regulation	The relation between average inflow to a reservoir and the (active) storage capacity of the reservoir.
Diversion reach	The length of river from which water is diverted, between the diversion structure and the tailrace; can also be called 'bypass reach' or 'dewatered reach'.
Downstream flows	The quantity, quality and timing of flows in downstream river reaches.
Environmental flows	The quantity, quality and timing of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being (some jurisdictions use related terms such as 'ecological', 'compensation' or 'minimum' flows).
Flushing	High-flow operations intended to move accumulated sediment from a reservoir and through downstream river reaches.
Geomorphology	The branch of science concerned with the features of the Earth's surface and their classification, description and origins.
Hydraulic rating	The relationship between flow volume and the amount and type of habitat provided during the passage of flow along a stream channel.
Hydraulics	The branch of science and technology concerned with the conveyance of liquids through pipes and channels; determines factors such as flow velocity and depth.
Hydrology	The branch of science concerned with the waters of the Earth, especially with the portion of the hydrological cycle from precipitation to re-evaporation or return to the water of the seas. Applied hydrology utilises scientific findings to predict runoff and for other water resources management applications.
Hydrometric networks	A group of data collection facilities and activities for different components of the hydrological cycle that are designed and operated to support water resources management.
Imbricated	Arranged in overlapping scales or plates.
Inflow forecasting	The prediction of future values of flow into a reservoir.
Minimum releases	The minimum flow permanently released from a project in order to meet environmental or other non-power water requirements in the downstream reach.
Natural flow conditions	Conditions without human influences or without alteration by a specific hydropower project; may also be called 'pre-project', 'baseline' or 'reference' conditions.

Peaking	The practice of releasing pulses of water to increase hydroelectric power production to meet peak electricity demand; may also be called 'load-following'.
Ramp rate	The rate of change in output from a powerplant. In a hydropower plant it is directly proportional to the rate of change in flow release, and is often subject to rules that determine the maximum allowable rate of change, in order to prevent undesirable downstream effects.
Release	Regulated flow through an outlet.
Re-regulating reservoir	A reservoir or pond located downstream from a hydroelectric plant, which has sufficient capacity to buffer the fluctuating discharges from the plant and to release them in a more uniform or natural manner downstream.
Residence time	The average amount of time water remains in a reservoir; can be approximated by the average volume divided by the average rate of inflow.
Tailrace	A channel or tunnel for conducting water away from the powerhouse after it has passed through it, into the river or an afterbay.

Kembs project and alluvial island restoration site connecting the Grand Canal d'Alsace with the Old Rhine on the border of France, Germany and Switzerland
Photo Credit: ® AIRDIASOL.Rothan



1

Introduction

Introduction

As hydropower projects store, divert and release water, they change river flows downstream of project-related infrastructure. **Downstream flows** are simply defined as the quantity, quality and timing of flows in downstream river reaches. Often the term ‘regime’ is added, to highlight that downstream flows are always variable over time. Changes to flow regimes can have positive and negative implications for river ecosystems and users.

Responsible developers, operators and regulators will make design and operational decisions with an awareness of downstream impacts and in consultation with downstream stakeholders. A fair and transparent process for understanding and balancing downstream impacts will facilitate public acceptance and access to finance, avoid business risks and open up business opportunities, and increase the economic viability and development contribution of a project. There is thus a clear business case for following good international industry practice on downstream flow regimes.

1.1 This How-to Guide

1.1.1 Aim

This How-to Guide aims to increase knowledge and understanding of practical measures that can be undertaken to meet good international industry practice, in conformance with the internationally recognised Hydropower Sustainability Tools (see Box 1).

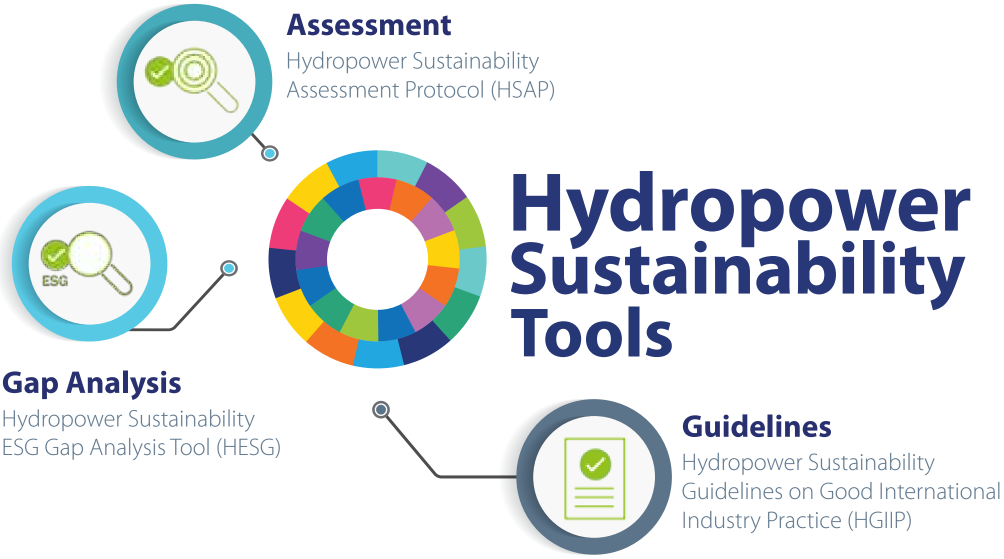
This guide expands upon the Hydropower Sustainability Good International Industry Practice Guidelines (HGIIP) and is designed to support practitioners and stakeholders in addressing downstream flow issues.

The key decision-makers for downstream flow issues are the hydropower companies that develop, own and operate projects, as well as various government agencies that are concerned with project licensing or water management. The guide can help decision-makers recognise downstream flow issues early enough to manage them responsibly. It can also help downstream stakeholders to engage effectively with upstream projects.

Using a river for hydropower inevitably means altering its character, as well as the water and ecosystem services it can provide downstream of the facility. Some of the implications for different values (such as power generation, public safety, water quality or biodiversity) are covered in more detail in other parts of the Hydropower Sustainability Tools, while this guide provides a framework for considering all downstream impacts in an informed decision-making process, and for arriving at balanced outcomes.

Balancing downstream impacts is challenging because it is a multi-objective, multi-disciplinary and multi-stakeholder process, which takes place at different temporal and spatial scales, and with divided responsibilities. This guide emphasises the decision-making process itself. It draws on technical knowledge from different disciplines, and in particular the **environmental flows** assessments described in Section 4.2; however, it is not intended to replace existing environmental flows reviews and guidance, such as from Poff, Tharme and Arthington (2017) and the World Bank Group (2018).

One aim of this guide is to clearly differentiate between downstream flows and environmental flows. These terms are not synonymous. Firstly, ‘downstream flows’ is primarily a descriptive term, while ‘environmental flows’ is prescriptive – understood as the flows that should be released to mitigate impacts and maintain values. Secondly, environmental objectives and impacts are only part of the relevant objectives and impacts.



Hydropower Sustainability Tools

Assessment
Hydropower Sustainability
Assessment Protocol (HSAP)

Gap Analysis
Hydropower Sustainability
ESG Gap Analysis Tool (HESG)

Guidelines
Hydropower Sustainability
Guidelines on Good International
Industry Practice (HGIIP)

The Hydropower Sustainability Tools are governed by the Hydropower Sustainability Assessment Council, a multi-stakeholder group of industry, government, financial institutions, and social and environmental NGOs. The tools are supported by the International Hydropower Association (IHA), the council's management body.

Sustainability guidelines

The Hydropower Sustainability Guidelines on Good International Industry Practice define expected sustainability performance for the sector across a range of environmental, social, technical and governance topics. Released in 2018, the 26 guidelines present definitions of the processes and outcomes related to good practice in project planning, operation and implementation. As a compendium, the guidelines are a reference document for meeting the expectations of lenders, regulators and consumers. Compliance with each guideline can be specified in commercial contracts between financiers and developers, and between developers and contractors. The guidelines are based on the performance framework of the Hydropower Sustainability Assessment Protocol.

Downstream Flow Regimes

The Downstream Flow Regimes good practice guideline addresses the management of downstream flow regime issues with the hydropower project or operating facility. Adherence to this guideline is measured using the HSAP and the HESG.

Further information

Visit Hydrosustainability.org

Assessment protocol

The Hydropower Sustainability Assessment Protocol offers a framework for objective assessments of hydropower project performance. It 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 own previous sustainability tools. Assessments are delivered by independent accredited assessors and can examine different stages of a project's life cycle. Evidence collected during an assessment is used to create a sustainability profile and benchmark performance against both good and best proven practice. The assessment protocol was updated in 2018 with a new topic covering hydropower's carbon footprint and resilience to climate change.

Gap analysis tool

The Hydropower Sustainability ESG Gap Analysis Tool enables hydropower project proponents and investors to identify and address gaps against international good practice. Launched in 2018, the tool is based on the assessment framework of the HSAP's environmental, social and governance topics.

It provides a gap management action plan to help a project team address any gaps and is divided into 12 sections that are compatible with both the IFC Environmental and Social Performance Standards and the World Bank's Environmental and Social Framework.

Environmental impact assessments, management plans and licences often do not cover downstream flows comprehensively. Looking at downstream flows only through an environmental lens is too narrow, just as a power-generation perspective is too restrictive. Section 4.2 describes how modern interpretations of environmental flows have expanded beyond the original focus on ecology, but still do not cover all social and economic flow impacts. The challenge for decision-makers is to identify and implement downstream flow regimes that meet multiple objectives at the same time.

In practice, environmental and social impact assessments (ESIAs) or specialist environmental flows studies are often where most information regarding downstream flows can be found. They are thus very useful tools for projects in the preparation stage. However, practitioners cannot always rely on ESIAs, as many older projects have never undergone such assessments; and if they have, the information is becoming more outdated year by year, as the average age of the world's hydropower fleet increases.

1.1.2 Approach and structure

The approach of this guide is to map out the necessary steps or deliverables that the hydropower developer or operator should take or prepare in order to meet good international industry practice, in relation to the project life cycle, from early concept through to detailed design, construction, and operation.

The guide is presented in five chapters and two annexes:

- **Chapter 1** – Introduction
- **Chapter 2** – Understanding downstream flow regimes in hydropower
- **Chapter 3** – Achieving good international industry practice
- **Chapter 4** – Strategies and approaches
- **Chapter 5** – Conclusions
- **Annex 1** – Bibliography
- **Annex 2** – Project examples

1.2 Downstream flow regimes in the Hydropower Sustainability Tools

The hydropower sector now has a suite of tools to deliver sustainable outcomes; they include the Hydropower Sustainability Assessment Protocol (HSAP), the Hydropower Sustainability Environmental, Social and Governance Gap Analyses Tool (HESG), and the Hydropower Sustainability Guidelines on Good International Industry Practice (HGIIP).

A separate topic on Downstream Flow Regimes is included in all three of the main HSAP tools, each of which corresponds to a project life cycle stage – preparation, implementation and operation – and requirements on downstream flows are also set out in the HESG. These provide definitions of good and best international industry practice in the management of downstream flows, in relation to criteria for Assessment, Management, Stakeholder Engagement, Conformance and Compliance, and Outcomes. Downstream flow regimes are always assumed to be relevant, and should thus be evaluated in any HSAP and HESG assessment.

The intent of the Downstream Flow Regimes topic is that:

- Flow regimes downstream of hydropower project infrastructure are planned and delivered with an awareness of – and measures incorporated to address – environmental, social and economic objectives affected by those flows.

1.2.1 Objectives of this How-to guide

The guide is designed to help the practitioner to:

- understand downstream values and potential impacts;
- avoid unnecessary negative impacts;
- minimise, mitigate and compensate for residual negative impacts, in a cost-effective manner;
- enhance positive impacts;

- balance positive and negative impacts to achieve and maintain stakeholder acceptance, regulatory approvals and access to finance.

The objective is to inform the reader on how to manage downstream flow regime issues throughout the project life cycle, using a range of strategies and approaches, and where to find further expertise and guidance. It is intended for those engaged in the development and operation of hydropower projects, as well as stakeholders with interests in these projects, and in the wider hydropower industry.

1.2.2 Scope

The scope of this guide covers:

- the basic good practice requirements for the management of downstream flow regimes, set out in the HSAP and associated tools;
- all stages of a project's life, from the early stage, through preparation, implementation and operation;
- all impacts resulting from the project on the downstream flow regime;
- all types of projects, including run-of-river, storage, pumped storage, cascade and inter-basin transfer projects.

The geographic scope of downstream flows assessment and management should extend as far downstream as there are noticeable and significant changes to the pre-project flow regime. This includes river reaches, both downstream of the dam or other diversion structures, and downstream of the **tailrace**. Project-specific data are thus required in every individual case, to determine the geographic scope.

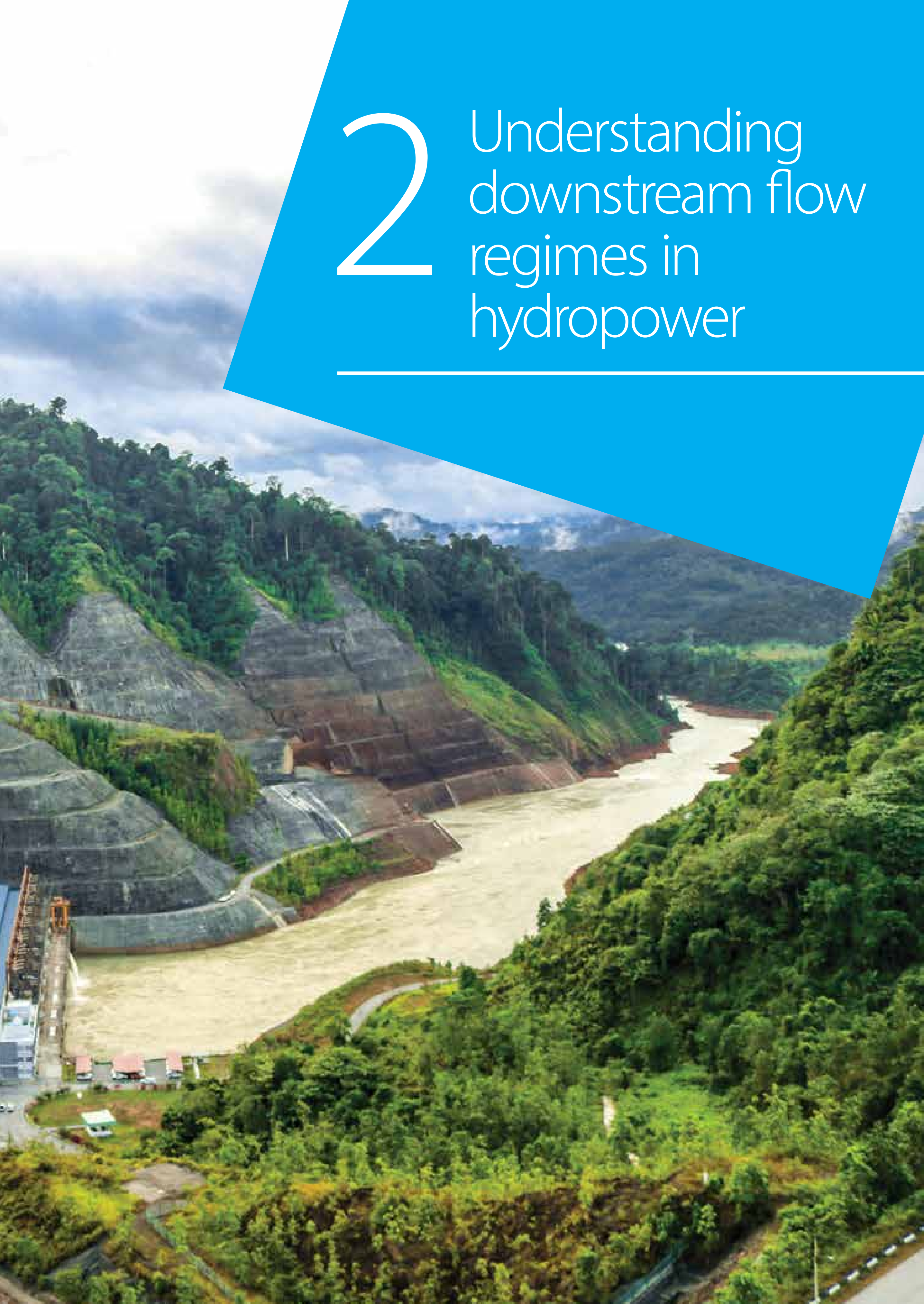
Where changes to flows have multiple causes, both the hydropower project's specific contribution to these changes and the overall cumulative impacts of the changes should be identified. While incremental change due to one particular project may be small, cumulative impacts may be of greater significance – particularly in basins with scarce water resources – and may require specific downstream flows arrangements.

As downstream flows are changed by projects, multiple different environmental, social and economic impacts result. For example, reduced flows in a diversion reach may not be sufficient to adequately dilute a given pollution load, thus leading to reduced water quality. Depending on the diversion reach, this may affect aquatic biodiversity, drinking water abstraction, irrigation, or other values.

The issues discussed in this guide thus have many overlaps with those in other sustainability topics. Generally, the Hydropower Sustainability Tools are structured so that some sustainability topics focus more on process and others more on content. In the example above, the water quality topic would cover the specific impacts of reduced water quality, while the downstream flow regimes topic would focus on the process of whether and how this change, alongside others, is taken into account in decision-making for project siting, design, operations and mitigation. For example, how is the need to dilute pollution taken into account when determining the outlet capacity of the diversion structure? Or is the opportunity cost of diluting pollution, in terms of lost power generation, large enough to instead motivate investment in upstream wastewater treatment?

Downstream flow issues are strongly related to reservoir planning and management, as downstream flows are often a direct consequence of reservoir releases. The reservoir planning or management topic would then focus on issues above the dam, and the downstream flow regimes topic on those below the dam. These two topics are also similar in that they both require balancing multiple interests and objectives. A particular reservoir management objective may determine flow release rules, or a particular downstream flow objective may determine reservoir management rules. For example, if the reservoir is maintained at the same level throughout the year because its most valuable use is for recreation, downstream flow volumes will be almost the same as they would be without the project.

Other related sustainability topics are hydrological resource management, focusing on **inflow forecasting** and management for generation purposes, and climate change resilience, which concerns longer-term adaptation to changing river flows.



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Understanding downstream flow regimes in hydropower

Understanding downstream flow regimes in hydropower

This chapter starts by describing flow regimes, their role for rivers and the effects of different types of hydropower projects on these flow regimes. This is followed by a review of the implications for downstream values and stakeholders, and of regulatory matters.

Navigation near Mandalay on the unregulated Ayeryawaddy River in Myanmar,
Photo Credit: Joerg Hartmann

2.1 Flow regime characteristics

A river's flow naturally varies, and its variations have a characteristic pattern. The **flow regime** can be characterised in terms of many aspects, such as flow magnitude, duration, frequency, timing, rates of change, and predictability. These are highly interdependent variables, which are sometimes combined into single metrics. For example, a common metric used to describe characteristic low flows, the average annual seven-day low flow, incorporates three variables: magnitude, frequency and duration.

The flow regime determines not just the volume, depth and velocity of the water, but also the temperature, sediment load, morphology, and many other physical and chemical parameters of the river. These in turn determine habitats for animal and plant species, and thus the ecology of the river and any associated floodplains, wetlands, groundwater-dependent ecosystems, and estuaries, with aquatic and riparian biotas adapting themselves to the flow regime. People living along the river also adapt their livelihoods, settlement patterns, infrastructure, and culture (e.g. with respect to recreational and religious practices) to the flow regime.

Hydropower developments result in changes to various aspects of the flow regime, depending on the project design and operational patterns. Compared to the pre-project hydrological regime, these changes can be seen in, for example, seasonally reduced flows or seasonally increased flows; rapid (i.e. hourly) increases and decreases in flows due to **peaking**; loss of (or changes to) flood events; and large flow events due to spills, **flushing** of the reservoir or of downstream reaches, or emergency drawdowns. For base load hydropower stations, discharges can be at a consistent flow for long periods; at peaking stations, flows can fluctuate rapidly on hourly timescales.

Flow changes affect the environmental, social and economic river uses, values and services along all affected river reaches downstream of the hydropower infrastructure. Stakeholders will have different objectives regarding these uses, values and services. Examples of ecological objectives include maintaining habitat for important species, e.g. critical spawning areas for fish or periodically flooded floodplain forests; examples of social objectives include ensuring public safety; and examples of economic objectives include reducing flood damages and maximising power generation. All these objectives are related to different elements of the flow regime.

Designing a balanced, broadly accepted flow regime can be challenging because some objectives may be well aligned, while others may contradict each other, and trade-offs need to be

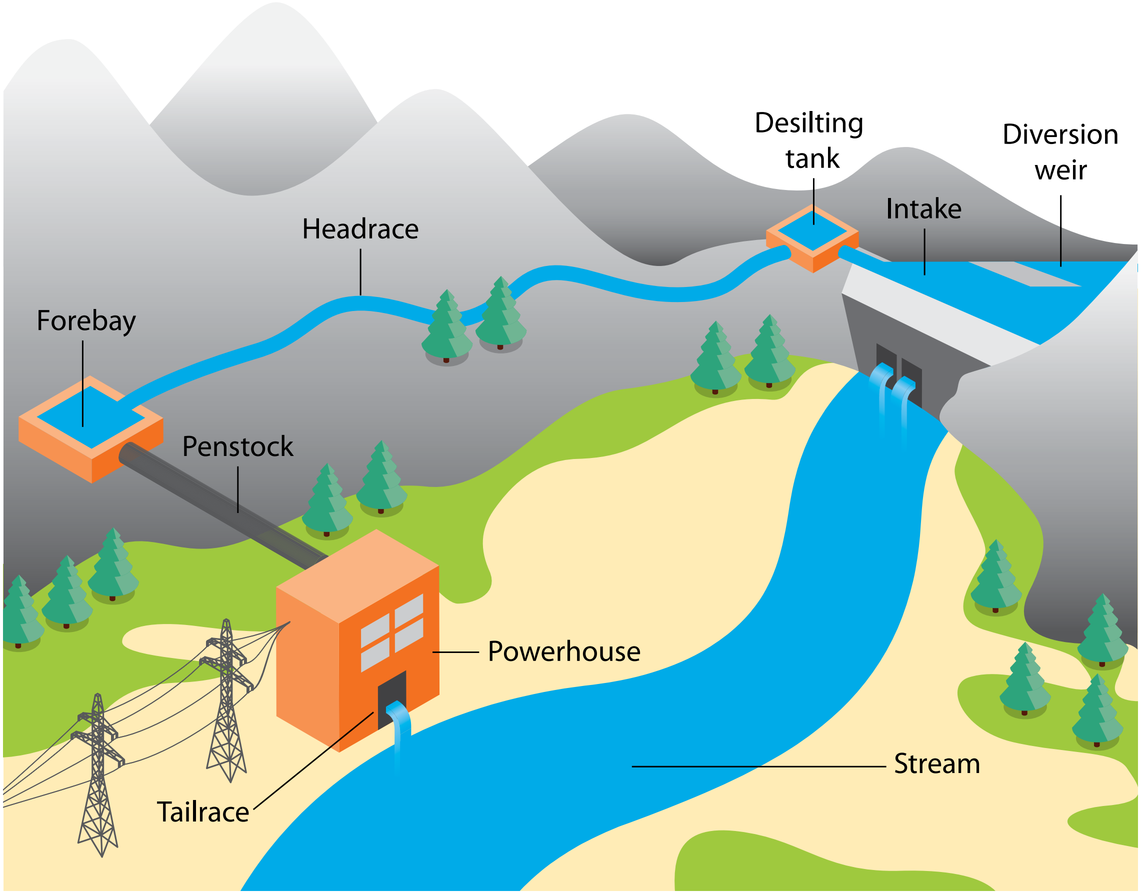

Figure 1. Schematic of a hydropower plant, with outlets at the diversion structure and the tailrace. Flows below the diversion structure and below the tailrace are influenced by design features and operational decisions[2]

resolved. Delivering flows that fulfil environmental and social objectives can have significant costs, not just for the operator but also for the general public: these include losses in revenue, taxes, royalties and dividends; and the need to replace some of the foregone generation by generation from other power plants, which have their own environmental and social impacts. Costs, benefits, and stakeholder objectives are also not static and will evolve during the lifetime of a project, changing aspects that were initially seen as balanced and broadly accepted.

In most cases, flows released from a hydropower project are compared to pre-project conditions (also called 'baseline' or 'reference' conditions). These are sometimes understood as **'natural' flow conditions**, i.e. conditions without human influences. However, in reality, the natural flow regimes of many rivers are no longer known. Their flows have long been and will continue to be influenced by a combination of upstream water abstractions and diversions, reservoirs, land use, climate change, and other cumulative anthropogenic impacts. In a longer timescale, flow regimes are also dynamic, being subject to natural climatic cycles. In addition, their ecological and socio-economic values may have been altered by other impacts such as pollution, overfishing, invasive species, or channel straightening. It is generally not advisable to assume that a pre-project flow regime was 'natural', and that therefore flow alterations from hydropower operations move the flow regime away from a natural regime, implying only negative environmental or social impacts. Hence, the incremental impacts attributable to the project need to be established on a case-by-case basis.

2.2 Modification of river flows

The degree to which hydropower projects can modify downstream water quantity and quality depends on the type of project. According to ICOLD's World Register of Dams, there are about 58,000 large dams, 6,100 of which have hydropower generation as their sole purpose, and 4,100 as one of their purposes.[1] Almost all of these projects will have some impacts on downstream flow regimes. There are no reliable global data on the number of smaller storage, run-of-river and inter-basin transfer projects, but these certainly include many tens of thousands of hydropower projects that have significant impacts on downstream flows.

2.2.1 Run-of-river projects

Even **run-of-river projects** (often defined as projects with an active storage capacity of less than one day of average inflows) can have significant downstream impacts, related to river diversions and to daily peaking operations.

In 'pure' run-of-river projects – those without any operational water storage or no active management of storage, and thus without peaking – impacts below the tailrace will be very limited. Some run-of-river projects on lowland rivers rely on large flows with a low head and with the powerhouse directly at the dam; by definition, these cannot cause substantial changes to downstream water quantity and quality.

In highland run-of-river projects, which rely on high heads, flow changes may only be noticeable in the **diversion reach**. In this reach, between the diversion structure and the tailrace, river flows are reduced and become more irregular, fluctuating between minimum flows and occasional spilling flows over the diversion structure. Consequently, the river's capacity to provide its functions (such as supporting aquatic life and local people, diluting pollution and transporting sediments) is reduced.

The effects of diversions can be mitigated to some extent by seepage, spillage, groundwater inflows and tributaries in the diversion reach, which restore some of the flow even without dedicated releases from the diversion structure. There is also an option to release flows to a diversion reach through an additional small hydropower plant at the diversion structure, if head and volume are sufficient.

Some highland river diversion reaches have limited biodiversity and no human settlements or pollution sources; in these cases, impacts are relatively low. Finding the right balance between flows that are left in the river and flows that are diverted through tunnels and the powerhouse should then be a relatively straightforward exercise.

Projects with small storage have short water **residence times**, and generally low potential to produce changes in water quality below the tailrace. Some large reservoirs are operated in run-of-river mode, where the water level is kept constant, at least for much of the year, to provide a high head for power generation or for other purposes (such as navigation or recreation). Although they do have a large storage volume (and thus potentially impact water quality), the inflows nonetheless equal outflows, and there is no material change of the natural flow regime.

2.2.2 Storage and pumped storage projects

Projects with large, actively managed storage capacity can cause intense flow alterations that reach far downstream, sometimes for hundreds of kilometres.

On some rivers, reservoirs can store several years of runoff, and make flows much more regular than under natural conditions. Seasonal regulation generally reduces flow variability, decreasing flows in the wet season and increasing flows in the dry season. This can affect all downstream environmental, social and economic values, dependent on seasonal variability.

On other rivers, peaking or 'load-following' operations can impose daily flow cycles and increase short-term variability. Hourly and daily peaking is possible even with small headponds or

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1 https://www.icold-cigb.org/GB/world_register/general_synthesis.asp

2 https://www.hindawi.com/journals/isrn/2012/730631/fig4/

forebays, in projects that are often still categorised as run-of-river. Some plants with limited storage may operate continuously in the wet season, but turn to peaking operations in the dry season, when they are constrained by water availability. Peaking operations have traditionally been required to meet peak power demand, often quite regularly during the same hours of the day. As more hydropower operators participate in deregulated 'spot markets', and as hydropower plants are increasingly required to complement and balance variable supply from solar and wind energy, releases may become increasingly variable.

Where storage is sufficiently large, short-term fluctuations from peaking can be superimposed on a seasonal regime of reduced variability, with even stronger downstream consequences.

There are many design options for pumped storage, some of which can affect downstream flows: this occurs if, for example, the lower reservoir is located on a river (an 'open loop' instead of a 'closed

Box 2: Downstream flow changes below the Gibe III project on the Omo River

The Gibe III reservoir (operational since 2015) has a volume of almost 15 km^3; the project was designed to operate as a peaking plant with planned releases of 800 m^3/s for 11 hours a day. As a result, major daily flow fluctuations were projected for large distances.

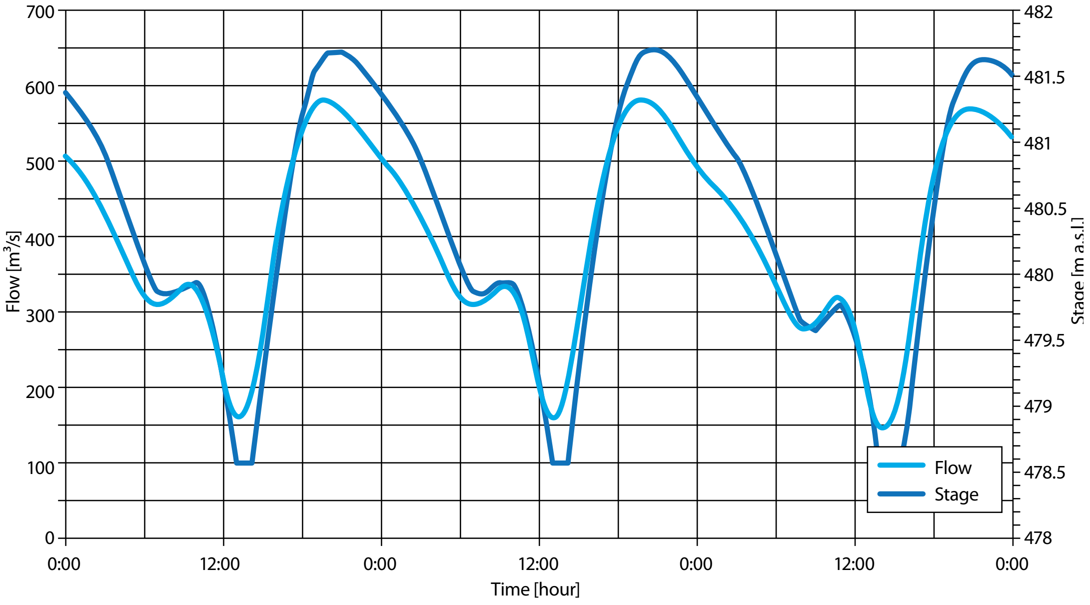

Figure 2. Daily flow fluctuations 200 km downstream of Gibe III, Ethiopia[3]

The large reservoir was projected to reduce seasonal flow variations, but some controlled seasonal flood releases were planned to mitigate the impact on flood recession agriculture on the banks of the Omo River.

In addition to direct changes to flow regimes, there can be indirect or secondary ones. The more regular seasonal flows allow major irrigation abstractions downstream of Gibe III, which would reduce total river flows. This is of concern because the Omo River is the most significant source of water for Lake Turkana, the largest desert lake in the world and a UNESCO World Heritage Site.

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[3] Agriconsulting SpA – Mid-Day International Consulting Engineers (2009)

loop' design) and has limited storage capacity (so that downstream releases have to be curtailed during pumping operations, and increased during generation operations). An increasing share of hydropower capacity is in the form of pumped storage projects, and managing downstream impacts from their operations will become increasingly important as this technology grows alongside variable renewables like solar and wind.

The most complex situations may be found in cascade developments, where cumulative flow changes come into play. In theory, cascades could be planned so that the most upstream reservoir provides regulation services, providing an even flow throughout the cascade, while the most downstream reservoir **re-regulates** flows to their pre-project patterns. The flow is then altered only in a limited reach of the river within the cascade. In practice, however, such well-coordinated cascade development and operations are rare, and cascades can be a major cause of downstream flow changes.

Even where re-regulation capacity is installed, it may only address some elements of flow alterations. For example, the planned Ganlanba project at the lower end of the Lancang cascade in China could re-regulate peaking releases from the next project upstream (Jinghong), but not the seasonal changes from the large storage projects further upstream (Nuozhadu and Xiaowan, with a combined active storage of 22 km^3). Particularly in countries with multiple developers, poor coordination between projects can also present problems regarding optimisation of power generation, sediment flushing, and safety of structures.

In countries with various generating companies, the dispatch of the different power plants is commonly organised by a separate entity according to the merit order, i.e. starting from the lowest-cost plants and progressively dispatching higher-cost plants until demand is met. In such cases, generators may not even have full control over releases from their reservoirs. The actual operations may be run remotely from central dispatch, and the local crew is only responsible for maintenance and safety. Unless objectives other than generation are formalised as constraints or agreements, the dispatch entity may disregard them.

Storage reservoirs affect not only downstream water quantity, but also its quality. Downstream water quality issues include anomalous gas concentrations (either supersaturation or de-oxygenation), anomalous water temperatures ('thermal pollution', either from warmer surface water or colder deep water), hydrogen sulphide, methylmercury, higher concentrations of nutrients and various pollutants, and toxic cyanobacteria. Algal blooms are a growing problem in many countries. Water quality issues are location-specific, and in some cases can also affect the river for long reaches. Smaller storage reservoirs and those used for pumped storage can have quality impacts during shorter timescales. For example, peaking operations can cause pulses of pollutants of higher concentrations, which may have entered the water from other sources, due to alternating low and high flows.

2.2.3 Inter-basin transfers

Where water is diverted from one river basin into another, power stations can deliver prolonged periods of higher than pre-project flows, while flows in the river system downstream of the diversion structure are reduced. For example, the pre-project flows in the Nam Theun River in Lao PDR ranged from 10 to 2,000 m^3/s, with an average of 238 m^3/s. Following construction of the Nam Theun II project, 2 m^3/s are now released as a minimum flow at all times, plus spills during floods. Up to 330 m^3/s are diverted through a tunnel and the powerhouse into the Xe Bang Fai River. On average, flows in the Xe Bang Fai have been nearly doubled, but the effects of additional inflows are mitigated as they first go through a regulating pond, and operations are stopped when the Xe Bang Fai is in flood. Changing flows permanently in both the diverted and the receiving rivers will cause major modifications in physical, ecological and social conditions. These will typically include changes to water quality.

2.3 Downstream values and stakeholders

In a hypothetical world with no other downstream values or stakeholders, hydropower projects would release water to maximise technical and commercial objectives, including generation, revenues and power system reliability. Projects would be designed and operated to avoid spilling, to maintain a high head, and to enable generation in peak demand hours.

After reviewing the typical release patterns from different types of hydropower projects, in this section we now provide an overview of typical downstream values and stakeholders, the effects that releases from hydropower projects can have on them, and some resulting constraints.

2.3.1 Power generation

Downstream power plant owners, their customers, employees and other stakeholders can be affected by flow changes. Most power plants benefit from regular river flows, either natural or released from upstream reservoirs. They include hydropower but also thermal and nuclear plants, which are mostly located on rivers because of cooling water needs, and for which the available quantity or temperature of cooling water can become a constraint on generation in dry and warm seasons. Downstream power plants can benefit from regulation at upstream plants operated for base load; but an upstream peaking plant can cause operational challenges.

Figure 3 shows how a downstream hydropower plant is affected by an upstream reservoir that evens out seasonal flows, by comparing flow duration curves with and without storage. When flows at the downstream plant exceed the intake capacity of 60 m^3/s, the upstream reservoir can store water that would otherwise be spilled, and release it when flows are below 60 m^3/s. The flow duration curve is flatter with storage than without. The value of upstream storage can be directly measured by the additional energy that is made available.

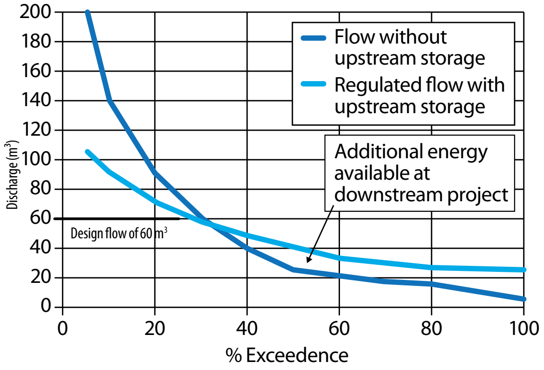

Figure 3. Flow duration curves showing power generation benefits of upstream storage[4]

Conversely, an upstream project that releases water only during peaking hours will force a downstream project to choose between investing in its own storage, generating when water arrives at its intake (which may be in the off-peak hours, depending on the time the water takes to move down the river), and/or spilling some of the inflow if it exceeds the intake's capacity.

Similar operational challenges can arise when upstream reservoirs release pulse flows, for environmental reasons or to flush sediments. In a cascade, such operations may need to be coordinated. For instance, sediment concentrations may be very high during flushing operations, with negative downstream impacts.

2.3.2 Flood management

Floods have caused millions of fatalities (for example, on China's Yangtze and Yellow Rivers) and billions of dollars in damage (for instance, an estimated USD 45 billion on Thailand's Chao Praya River in 2011). In many regions of the world, floods are expected to become more frequent and larger (due to anthropomorphic climate and land-use change), as well as more destructive (due to increased exposure of humans and property along rivers). Large floods can also cause environmental damage, for example by causing pollution from flooded industries or by damaging wetland habitats. At the same time, floods have

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[4] Hydro Tasmania (2007)

useful natural functions, and river ecosystems often quickly recover even from large floods; thus, it can be desirable to release controlled floods (also called 'pulse flows' or 'flushing flows') from time to time, to simulate natural floods (see Section 2.3.6).

One purpose of a hydropower reservoir may be flood control. Optimising the management of a reservoir only for flood control essentially means to permanently keep it as empty as possible, or to empty it in time before floods. The main operational challenge in a pure flood control reservoir is to shave off the most damaging part of a flood, its peak – and this requires predicting the time and duration of peak flows. If the peak flow is overestimated and the reservoir does not fill up, some flood control benefits are not realised. If the flood is underestimated and the reservoir fills up too early, the rest of the flood will have to be passed through. If very large floods are predicted, exceeding the reservoir's capacity, operators may choose to leave a flood buffer that allows flexibility of operations, in order to ensure safety of the structures under all conditions. During flood emergencies, public agencies sometimes assume authority over operations.

Downstream of the reservoir, flood attenuation will increase the safety of lives and property in most situations. As people adapt to reduced flood risks, floodplains may be opened up for more intensive use, such as permanent settlements and cropping. When smaller floods are controlled, a false sense of security can develop, and damage can be magnified when larger floods occur. The largest floods – such as those in Pakistan in 2010, which displaced some 20 million people – will overwhelm the capacity of any reservoir system. Even if the Tarbela reservoir had been empty, the peak flows of about 35,000 m^3/s would have filled up its live storage within approximately three days.

Two other factors complicate the relationship between reservoirs and floods:

- The reduction of flood releases results in reduced sediment scour, riverbed coarsening, and vegetation and infrastructure encroachment. For a certain level of flow releases, downstream water levels may then not drop as expected, because of these riverbed and floodplain changes.
- Large volumes of water may need to be released in emergency situations to maintain dam safety, and dam breaks (although of very low probability) could result in especially devastating floods. Even reservoirs that are not operated for flood attenuation need dam break and emergency management plans to protect downstream people, infrastructure and other values from severe flood releases (cf. How-to Guide on Infrastructure Safety, IHA, forthcoming).

A reservoir that provides a flood control service as well as hydropower generation should be designed and operated differently from a pure hydropower project. In order to optimise storage capacity and temporal storage allocation, the loss of hydropower revenue (from emptying the reservoir in anticipation of floods, thus lowering the head and, in some cases, losing water) needs to be balanced with the reduction in expected flood damages. Regulatory rules may be required to ensure that enough flood storage capacity is maintained for flood protection.

Flood protection should be achieved not just through reservoir storage, but also through a combination of early warning and evacuation systems, dykes and other downstream control structures, flood retention areas, more resilient downstream infrastructure, property buyouts, changing crops, flood insurance, etc.

The Three Gorges dam on the Yangtze River, for example, was built primarily for flood control. It has been suggested that it could generate significant additional revenue from hydropower if its operating rules were changed to reduce the flood buffer before the high-flow season and raise the head of the power plant. Such increased revenues could pay for other means of flood protection (such as dykes, relocation of infrastructure, or flood insurance for farmers). From a flood management perspective, it is possible that the overall outcome could be improved. The pattern of downstream flows would be closer to pre-project conditions, possibly leading to improved ecological outcomes. For example, the wetlands along the lower Yangtze would receive a seasonal flow pulse, and at the same time they would retain some of the flood waters.

2.3.3 Irrigated agriculture

Food security depends on farmers, and farmers depend on water for food production. In turn, water availability depends on land use. Whether rainfed or irrigated, any form of agriculture influences surface flows and aquifers, potentially affecting downstream water users, including hydropower stations. For example, agriculture significantly reduces inflows into the Mtera reservoir, which is one of the key components of Tanzania's power system. There has been a long discussion in the Great Ruaha basin regarding how to change agricultural practices in order to sustain power generation.

Demand for irrigation water is expected to continue to grow, for a number of reasons: population growth, higher incomes enabling better nutrition, increasing scarcity of arable land (which requires intensification of land use), and climate change (which increases crop water requirements in many areas). An expansion of irrigation is often equated with increased storage in reservoirs. However, in recent years, large-scale public surface irrigation schemes served by barrages and dams have stagnated or actually shrunk, for example in South and Central Asia. Meanwhile, groundwater-based irrigation with individual pumps has been booming, often supported by subsidised electricity. Where pumping exceeds sustainable levels and groundwater levels go down, river levels may be indirectly affected.

Where irrigation is served by upstream dams, water can either be taken directly from a reservoir, or from the river or a canal downstream of the tailrace. In the case of direct irrigation water abstraction, the abstracted water cannot serve for power generation, and irrigators and hydropower generators have separate water intakes. In the case of downstream irrigation water abstraction, the water can first go through the powerhouse. However, the dam operator is often an irrigation district or water resource agency, and the release schedule is determined by seasonal irrigation demand; thus, hydropower generation is a secondary concern. If water is scarce and valuable, the reservoir may release water only during the main growing season, and hydropower is generated only during that same period. This may lead to very low load factors, making hydropower financially unattractive.

2.3.4 Navigation

Owners of river boats and ships, their customers, employees and other stakeholders can be affected by flow changes. Inland waterways offer some of the most convenient and fuel-efficient transport routes, especially for bulk cargo, and the demand for transport services is bound to increase with economic growth. Small-scale navigation is also important for local mobility and livelihood activities such as trading and fishing, particularly in countries with poorly developed road networks.

Navigation requires a certain river flow and depth. Enabling navigation over rapids, sandbanks and other natural impediments may be one of the primary benefits of a multi-purpose hydropower project in some river systems. The retention of sediment in upstream reservoirs can also reduce the need for dredging, and increase the navigability of inland waterways.

In some lowland rivers, particularly in Europe, the US and China, dams are operated to release flows in the dry season to enable navigation; they may also be equipped with locks to allow long-distance transport. Releases in the dry season to maintain a certain river depth would tend to be compatible with baseload hydropower generation during the dry season. Peaking operations, on the other hand, can disrupt navigation.

2.3.5 Water supply

Domestic water demand from rural residents typically has a minor influence on water resources; such water is not directly abstracted from reservoirs or from rivers affected by upstream hydropower, but from local springs, streams and wells. (In some cases, these can be affected by hydrogeological changes due to hydropower projects.) However, the residents of large-scale urban areas and their industries can require substantial amounts of water. Their water consumption is also very valuable in economic terms, and has high reliability requirements; it is thus often sourced from reservoirs.

The implications for hydropower generation depend entirely upon the configuration of specific supply schemes. Where urban water abstraction is downstream of a hydropower project, on a river with variable flows, there may be a strong additional argument for flow regulation and increased dry season releases, compatible with baseload generation. Where urban water abstraction is directly from a reservoir, water available for generation and for downstream releases is reduced. There are even cases where water supply is combined with pumped storage. The pumps at the Palmiet pumped storage scheme in South Africa can refill the upper reservoir, either for power generation or for transferring water from the Palmiet River catchment to the Cape Town water supply system.

2.3.6 Biodiversity

Downstream ecosystems and the services they provide are strongly determined by downstream flows. Flows and their natural variations over time can be seen as the ‘master variable’ that governs all other variables in a freshwater ecosystem.

The short-term, seasonal and inter-annual flow variations in a river are an important element of aquatic habitats. Many fish species are adapted to migrate and spawn when certain flow rates, levels of turbidity or temperatures are reached. Low flows have their own ecological role and may, for example, enable use of sandbanks for nesting by river turtles. High flows may be required to overcome natural barriers or to temporarily access the floodplain. Flow variations also affect amphibious and terrestrial species that use rivers, lakes and wetlands at least temporarily.

Floods of varying magnitudes influence the movement of sediments with different grain sizes in the riverbed, which provide various types of habitat for instream biota. In the absence of floods, riverbed sediment deposits will change (e.g. becoming clogged, **imbricated** or armoured), thus reducing their functionality as habitat or breeding areas. Species diversity and abundance may decline, and non-native species may come to dominate the river. Vegetation may encroach into the floodplain and channel, impacting on natural riparian vegetation habitats and increasing floodwater retention. Large floods, although often destructive from a human perspective, can have beneficial long-term effects for ecosystems, such as channel formation, sediment movement, floodplain replenishment and aquifer recharge.

Aquatic life will also find it difficult to survive below peaking hydropower plants; for example, fish are trapped in shallow pools when flows suddenly drop. A lack of sediments and nutrients in downstream releases, as well as changes in temperature, dissolved gases, etc., may also affect aquatic life, even extending into coastal waters.

Because rivers are such diverse, dynamic and often poorly understood ecosystems, it is difficult to predict the response of each individual species to flow regime changes. However, the large majority of studies on ecological responses to flow modifications show negative effects on species diversity and abundance. The natural flow generally results in a more diverse, productive and resilient downstream ecosystem than a modified flow regime.

This assumption is not universally valid, though, as some natural flow regimes are highly variable, with naturally low diversity and low productivity, and the species present have adapted to these regimes. In these cases, when flow variability is reduced, diversity and productivity can actually increase, but often because of invasive or non-native species.

For some species and ecosystems, conditions may improve as a result of controlled releases from a reservoir. For example, drawing water from deeper layers in a reservoir can cool down a river, delaying or cancelling out climate change effects. A retrofit of the intake system on the Shasta dam in California enabled such cool water releases, thus improving downstream salmon habitat. Also as a result of climate change, other rivers could become dry or be damaged by unnaturally large floods, without flow regulation by hydropower reservoirs.

2.3.7 Fisheries

On some rivers, fish (and some other aquatic organisms) are important sources of protein for subsistence and of cash income for commercial fishermen. The global inland fisheries catch is estimated at 12–17 million tons per year, and the number of inland fishers is estimated at 17 million, with another 8 million employed in post-harvest activities. The annual value of the inland catch, based on first-sale prices, is estimated at up to USD 43 billion.

Fish stocks are influenced by many factors, including fishing pressure, pollution, regulations, invasive species, and interrupted connectivity. It can be difficult to attribute reductions in fishing yields to one specific factor such as flow releases, partly because baseline studies on fish stocks and their socio-economic relevance, and data on the response of different fish species to flows, are often lacking. Therefore, in rivers with important fisheries, efforts to survey fish stocks and define flow regimes that will help maintain these populations should be part of a suite of fishery and fish biodiversity support measures.

2.3.8 Social values

Local communities, especially indigenous peoples, can have strong cultural connections to rivers. Natural river flows can be important, not just for material livelihoods and standards of living, but also for quality of life in a broader sense, including a sense of place, cultural identity, spiritual well-being, religious sites, and rituals such as riverside cremations.

Seasonal flow changes can provide the cues for livelihood activities (e.g. planting, fishing) and cultural activities (e.g. boat festivals) throughout the year. Natural geomorphic features in a river (e.g. waterfalls, canyons, pools) can be important cultural sites for local communities, and can have a significance that may not be well understood or appreciated by those who are not part of that community.

Recreation along riverbanks, on the river itself, on downstream reservoirs, and on beaches close to river mouths can be affected by downstream releases. In many places, fishing, rafting, kayaking and other river-related activities are becoming a more popular part of local recreation and tourism. Rough estimates show that perhaps 200 million people in the world are recreational fishers (i.e. the fish they catch are not their primary resource to meet basic nutritional needs, and are not generally sold or traded). The non-market use value of this activity may be about USD 70 billion, based on direct expenditure by fishers (licences, boats, gear, etc., but not even counting travel expenditure).

The aesthetic appeal of rivers can be strongly affected by flow releases. For example, a waterfall may be diminished if a river is diverted around it. In some places, primarily in North America and Europe, downstream releases are conditional upon the interest of users (for example, releases for kayaking or over a waterfall during summer weekends). While such measures can be important for short-term visitors and tourism operators, for local residents the aesthetic and recreational quality of a river may depend more on the longer-term flow regime.

The safety of any downstream river user mentioned in Section 2.3 – for example, a recreational angler or boat operator – may be affected by short-term fluctuations in water levels caused by peaking operations, as well as by flood and sediment flushing releases, especially when these fluctuations are unexpected or poorly understood by the user. The associated risks depend on the hazard (e.g. rate of flow increase), exposure (e.g. number of people in, on and near the water), and the users' vulnerability (e.g. whether they are able to swim); such factors determine the required risk mitigation measures, such as **ramp rates** and warning systems. For example, during the tourist season in France, EDF assigns seasonal guides to raise awareness of safety issues among river users.

Public health in downstream communities can also depend on flows, especially with regard to safe water for domestic use and for recreation. For example, reduced flows can decrease groundwater recharge and interrupt springs used for drinking water, or can increase pollutant concentrations in surface water and trigger algae blooms. On the other hand, high flows can flush pollutants from point or non-point sources into rivers.

2.3.9 Fluvial and coastal geomorphology

A river with a natural flow regime is approximately in a sediment transport equilibrium, i.e. over time the amount of sediment arriving from upstream equals the amount carried away downstream.

Retaining sediment in reservoirs over time leads to **geomorphological** changes downstream. Rivers will tend to deepen their bed (incision) and to erode their banks, which can lead to changes in channel forms and habitats, as well as potential losses of land, and of infrastructure such as bridges. Changes can reach all the way downstream to estuaries, deltas and adjacent coastal stretches, where sandy beaches are no longer naturally replenished and land may subside, thus making it more vulnerable to erosion by rising sea levels. Many different stakeholders can be affected.

The patterns of releases from reservoirs determine how much of the sediment can be flushed through them, and how much sediment is mobilised and transported downstream. Much of sediment transport takes place during flood events, and as described above, these can be reduced by hydropower projects. Depending on management objectives, **controlled flood releases** may be desirable or not. If riverbank erosion is already a significant problem, it may be exacerbated by flood releases. However, if sediment accumulation is the main problem, and the channel needs to be flushed out, high flow releases become desirable.

The Yellow River, which has the largest sediment load of any river in the world, and the Colorado River are two examples of rivers where water managers have been experimenting with high flow releases to move sediment downstream. For any flow regime adjustments to manage sediments, it is important to understand the broader array of benefits to the river system that natural sediment processes provide, such as for biodiversity and for sand or gravel extraction (see also Box 3, Section 4.2.2).

2.4 Current legal, regulatory and bank safeguarding instruments for downstream flows

Under national and international law, different types of downstream water rights have to be respected by upstream water users, including reservoir operators, especially in conditions of water scarcity.

First to be considered is the human right to water. This is being increasingly accepted through national constitutions and legislation, as well as United Nations documents, which state that everyone is entitled to "sufficient, safe, acceptable, physically accessible and affordable water for personal and domestic uses". Consistent with this principle, in most water resources regulations, domestic consumption is given first priority as a water use category. While the human right to food also requires access to water (for agriculture, fisheries and food processing), this is generally given a lower priority. Water licences for users with lower priorities or reliability levels will be conditional on the water being available, after the higher levels have taken their requirements up to their allocated rights. In more recently reformed water laws, the environment often also receives an allocation informed by environmental flow studies or basic principles enshrined in the act. South Africa's 1998 Water Law was one of the first to allocate a proportion of water to protect aquatic ecosystems.

Water laws in many countries define rules for allocating water ownership or usufruct rights for productive or 'beneficial use' to individuals, communities and businesses. For example, in the eastern United States, riparian landowners (those owning land adjacent to a river) typically have senior water rights, while in the western US, those with a prior appropriation (who claimed their water rights first) have senior water rights.

Upstream water managers and reservoir operators have to take these rights into account when they plan flow releases. Treaties and agreements on the management of transboundary rivers typically also contain some measures that protect downstream users from the harm that could be inflicted by unilateral decisions of upstream countries.

The relevance of these rights is illustrated by major rivers such as the Yellow, Colorado, Indus and Murray, which have at times fallen dry before reaching the sea, thus depriving downstream stakeholders and ecosystems of water. The lakes in several interior basins, such as the Aral Sea, are also at risk of drying out because of reduced inflows. Hydropower 'consumes' water directly through evaporation from its reservoirs (where the rate of open water evaporation is higher than the rate of evapotranspiration from the vegetation replaced by the reservoir). Also, by regulating flows, hydropower can indirectly contribute to increased water abstraction. The initial filling of some hydropower reservoirs can also affect downstream stakeholders significantly, as illustrated by the ongoing negotiations between countries on the Nile River over the filling of the Grand Ethiopian Renaissance Dam.

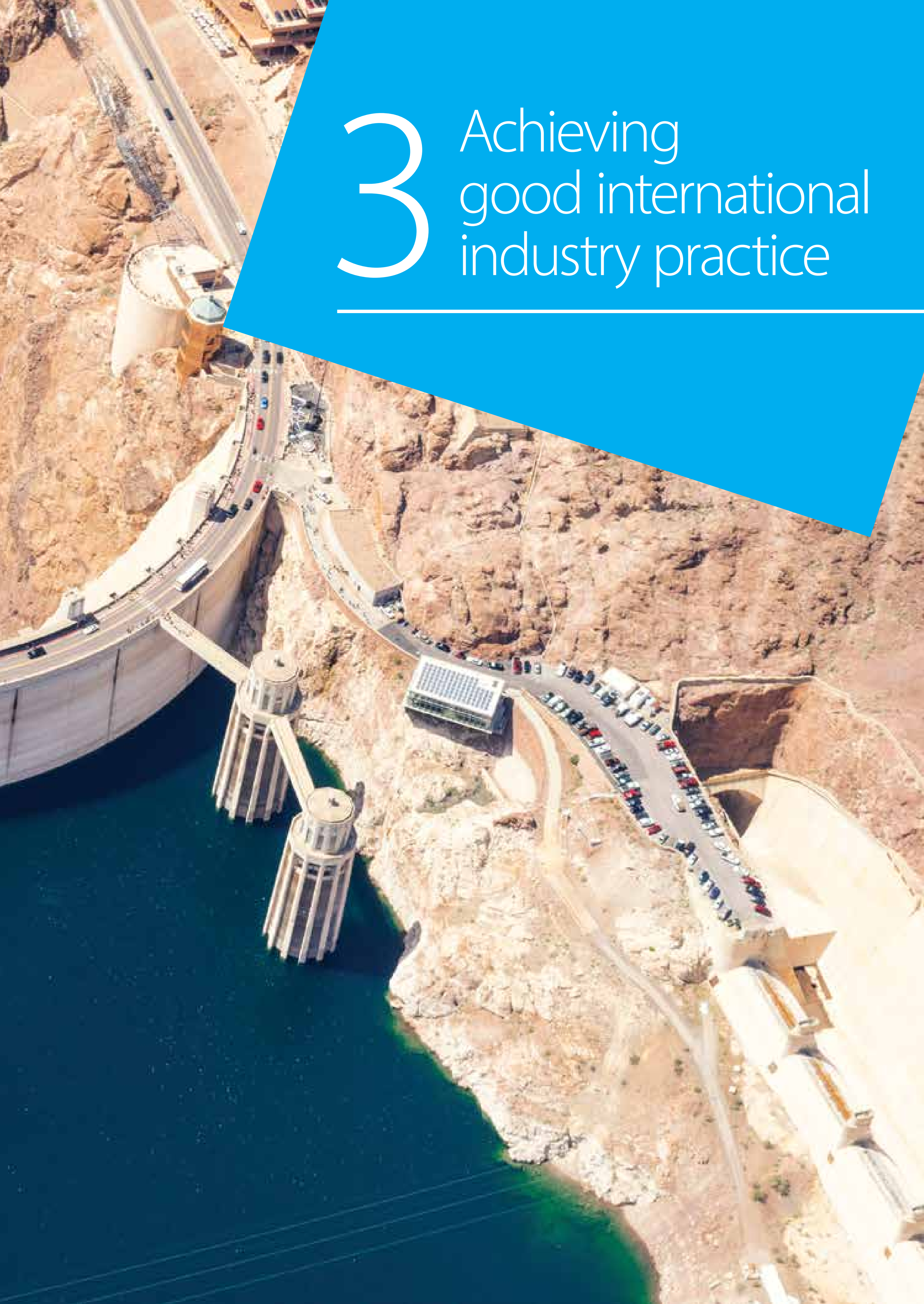
In practice, the releases required to satisfy downstream rights are usually regulated through project-specific rules for reservoir management and/or downstream releases, in environmental and operational licences and concession agreements. These rules may address a number of other downstream considerations, such as ecosystem conservation, navigation and flood control. For example, they may impose limits on minimum flows, maximum flows and ramp rates (up and down), and place timing (e.g. seasonal) or trigger (e.g. inflow levels) conditions on release requirements.

As regards environmental licensing, many countries in recent decades have introduced national rules for environmental flows. In China and France, for example, a minimum of 10 per cent of annual average flows has to be released at all times. Mexico's National Water Plan calls for the establishment of basin-by-basin environmental flow reserves, a process that is ongoing. Peru requires project-specific environmental flow studies. The European Union's Water Framework Directive has established quality and ecological objectives for rivers, which cannot be achieved without adequate downstream flows releases.

Some countries have requirements for periodic re-licensing, when downstream flows rules can be updated based on growing understanding and changing societal preferences. Most countries recognise the importance of environmental flows in principle, for example in national water laws, policies and strategies. However, an implementation gap still exists, often based on a lack of technical capacity to determine and enforce water requirements, in combination with vested interests in particular downstream flow arrangements.

It is noteworthy that many legal and regulatory requirements refer to river basins as the appropriate framework for managing downstream river impacts. Hydropower developers and operators thus have to invest some effort in understanding their river basin setting.

Compliance with national legal and regulatory requirements is mandatory. If developers choose to seek funding from particular sources, they may become subject to additional requirements. There are no specific rules on downstream flows in the safeguards of development and commercial banks. However, many of the issues described in this guide are covered, for example by the World Bank Group's standards on biodiversity, pollution, community health and safety, displacement, cultural heritage, and indigenous peoples; furthermore, projects on international waterways are subject to additional requirements to qualify for World Bank funding (see Section 4.7).



3

Achieving good international industry practice

Achieving good international industry practice

The Hydropower Sustainability Tools provide definitions of current good practices for downstream flows. Chapter 3 of this guide links downstream flow regimes to the tools, which are structured by different stages in the project life cycle and by different criteria for each stage. This structure helps to identify specific steps that should be taken to achieve good practices. The responsibility for taking these steps and attaining good international industry practice clearly lies with the developer and operator of a hydropower project, even if certain tasks can be outsourced to consultants and contractors, and if government agencies assume certain roles.

Public safety around the
dam in the Trevallyn project
in Australia
Photo credit: Joerg Hartmann

3.1 Downstream flow regimes in the project life cycle

Downstream flows are a relatively recent concern; historically, downstream impacts were often an afterthought. During project planning, the implications of siting, design and operational decisions for downstream flows were often only considered if there was a physical or regulatory constraint. Environmental and social impact assessments, if undertaken at all, were limited to a narrow geographical area, and disregarded impacts further downstream. Stakeholders were expected to adapt to any changes in river flows imposed by upstream projects. Many dams were built to provide a more stable river flow, which was considered an inherently good thing that did not need to be evaluated in detail. Over time, many countries introduced **minimum release** rules, to ensure that at least some water remained in the river. However, the amount released was typically not based on specific water requirements downstream. These approaches are clearly no longer acceptable, and sufficient experience has now been gained to deliver better outcomes, both for new and for existing projects.

As a hydropower project moves through the different stages in its life cycle, the downstream considerations evolve. Initially, at the early or identification stage, there are multiple options for project siting, design and operations, with a very broad range of potential downstream outcomes. These options are progressively narrowed down as a project moves through the preparation, implementation and operation stages.

Many decisions regarding future downstream flows are made in the preparation stage, and the future ability to deliver well-balanced downstream flows largely depends on decisions made at this stage (e.g. dam design, power purchase agreements, mitigation measures, etc.). Developers need to understand that the definition of a downstream flow regime is an iterative process, involving multiple, overlapping and sometimes conflicting interests, and that an upfront investment of time and resources may be more time- and cost-effective than any attempt to defer such investment, in the hope that it will not be required.

Decisions made in later project stages also have important impacts. The construction stage presents particular issues with respect to river diversion and reservoir filling. During operations, practical experience can be gained to enable an operator to test predictions of downstream flow impacts, and to make adjustments to operational plans, and in some cases to infrastructure. As the average age of hydropower plants continues to increase, an increasing number of operating plants are facing changing downstream conditions and demands for re-operation.

3.1.1 Early stage

In the early stage, hydrological investigations will begin to consider factors that will ultimately be part of the considerations for downstream flows. The following steps should be taken with respect to downstream flow regimes:

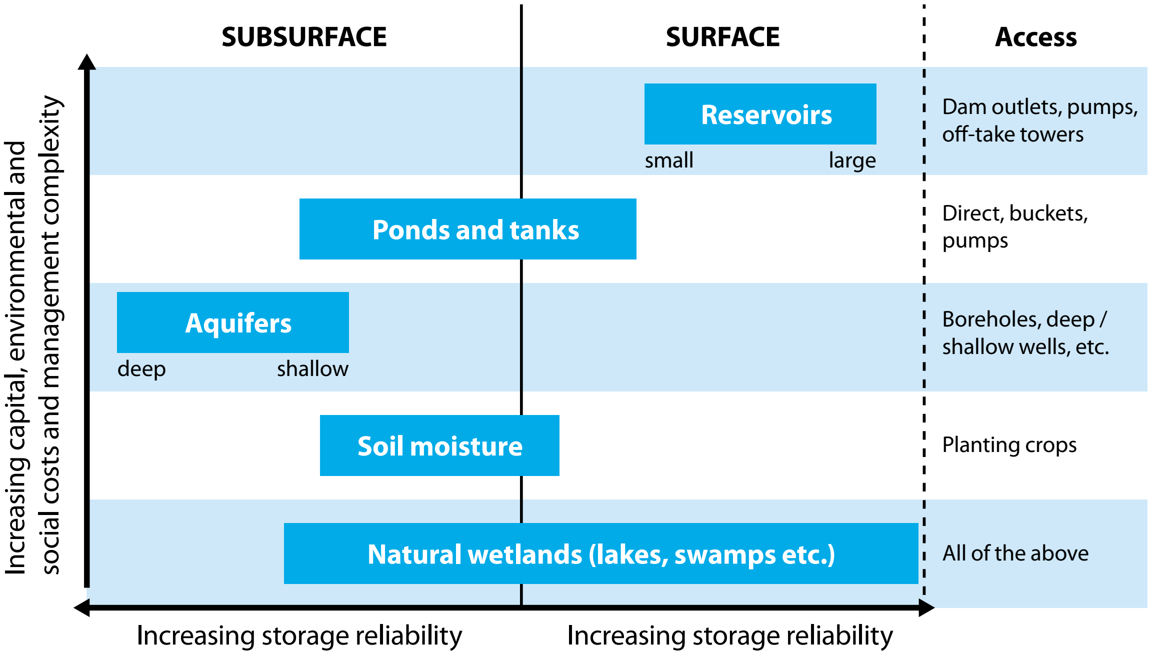
- Identify and compare flow needs and flow delivery options for potential sites and designs at a pre-feasibility or scoping level, without detailed data. This high-level evaluation of downstream values and uses, and examination of experiences from other project developers with respect to downstream flows, should help inform consideration of project options.
- Identify policy and legal requirements and ongoing reforms regarding flow regimes and water licensing.
- Consider trends for other water uses that may influence power operations over time, such as new or expanding industrial, agricultural, forestry or recreational water uses, as well as inter-basin transfers.

Key information sources may be hydropower masterplans, river basin development plans, and strategic environmental assessments. The focus in this stage is on understanding different options for sites and designs, including whether water storage is required, what capacity and type of storage (based on an investigation of the power market), the potential operational role of the project, and non-power interests in water storage. Water storage is likely to become more important in the future, because of:

- economic and population growth, which increases the demand for water services;
- climate and land use change, which increase the variability of inflows;
- variable renewables, which increase the need for back-up sources of power, and potentially the value of peaking.

However, given the costs and impacts of building reservoirs, including those arising from the alteration of downstream flows, it is necessary to consider realistic alternatives to reservoirs. If maintaining stable dry season flows is important

Figure 4. Water storage options[5]



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[5] McCartney and Smakhtin (2010)

for many water uses (including power generation), healthy catchments with natural soils, forest cover, wetlands and aquifers may be as effective as an upstream reservoir. Healthy catchments typically provide much more stable flows and much less sediment than degraded catchments, although the total annual water yield may be slightly reduced because additional vegetation causes an increase in evapotranspiration.

The main differences among storage options are in their costs (both monetary and external), management complexity and storage reliability. Different storage options, or the decision to forego built storage and rely on a run-of-river design, will all have different implications for downstream flows. In the early stage, the ecological and social implications are likely to be reviewed from a scoping perspective, with regionally available information (e.g. typical regional river characteristics, values and uses, and cumulative impacts from other developments), and not yet with site-specific analyses. An initial gap analysis may be undertaken to identify the hydrological, ecological and social surveys and studies that would become necessary in the next stage. If baseline information is limited, it is advisable to start monitoring programs already at this stage, such as by installing flow gauges.

If a promising project site and type have been identified, the project moves into the preparation stage.

3.1.2 Preparation

During the preparation of a hydropower project, the following steps should be taken with respect to downstream flow regimes:

- documentation of the current downstream baseline conditions and their relationships with the pre-project flow regime;
- identification of potential flow changes downstream of the project infrastructure;
- evaluation of any economic, environmental and social effects of these flow changes;
- potential mitigation measures to address these impacts.

These steps are familiar from typical environmental and social impact assessment (ESIA) methods, and indeed, downstream flows studies can fit well into an ESIA. However, in different contexts, ESIAs may or may not cover all of the downstream impacts. For instance, they may be more focused on environmental aspects, but less so on social aspects, and even less on economic aspects. They may emphasise the mitigation of negative impacts over the enhancement of positive impacts. They may or may not include a framework for balancing impacts and evaluating trade-offs. Moreover, they may or may not include environmental and social management plans (ESMPs). Therefore, ESIAs and ESMPs may only partially cover the necessary preparation work for downstream flows, often with a focus on the environmental flows aspects. Other parts will need to be covered in other studies, such as in overall feasibility studies, in dedicated downstream flow studies, or in operational plans.

While this separation can be less than ideal, in many cases it is inevitable because government regulations narrowly prescribe the scope of ESIAs and ESMPs, sometimes with standardised Terms of Reference for hydropower projects. Developers then have no choice but to follow the standard. Ultimately, the format of preparatory studies should not matter as long as the substance is covered. The preparation steps should reflect the following good practices:

- Consider all potentially affected river reaches for which flow changes (regarding volume, timing, quality and sediments) can be attributed to the project.
- Consider options for flow ranges and variabilities, in terms of their implications for different objectives and issues that have been identified by studies and stakeholders.
- For particularly complex situations, a cumulative impact assessment may help manage competing interests and other development trajectories that will have implications for water rights and downstream flow requirements.
- Consider all stages of the project, including average, infrequent and extreme inflow and operational conditions. The assessment should thus include special periods such as reservoir

filling, extreme hydrological conditions such as droughts and floods, and potential long-term runoff trends due to climate change.

- As the preparation stage progresses, increasingly improve the downstream flows assessment through hydrological and hydraulic modelling as well as other elements of the feasibility studies. The assessment should run in parallel with the different engineering design stages, up to detailed design. An iterative approach with co-ordination between engineering, financial, environmental and social studies is vital for achieving successful outcomes, including a willingness to review project objectives in a flexible manner. (In reality, engineering studies often precede environmental, social and other downstream studies by years, making iteration, flexibility and design adjustments difficult; this is one of the most frequent causes of unsatisfactory outcomes.)

- Follow a methodological and defensible process to determine links between flows and objectives, and to reach a downstream flow regime commitment. No specific methodology is required to meet international good practice; regarding environmental aspects, Section 4.2 reviews a number of methodologies that may be appropriate, depending on project-specific context, objectives, and data availability.

- Address trade-offs among competing ecological, social and economic objectives, and seek outcomes with the lowest impact and highest benefit. This requires a process of stakeholder engagement, which in any case should be an integral part of the ESIA/ESMP process.

- To deliver the release commitments, design suitable locations, capacities, controls and monitoring devices for water intakes and outlets. Flexibility and adaptive management over time need to be enabled through design features; for example, through the technical ability to change releases rates (e.g. to regulate the flow rate through an outlet).

- Where appropriate and cost-effective, identify additional measures to protect downstream values or compensate for impacts. Downstream flow-related issues may or may not be resolved entirely through dedicated flow regimes, and residual impacts often remain. Additional measures will typically be complementary to dedicated flow regimes.

These processes will take time; in some cases (where few baseline data are available) years. They will thus have to be programmed as early as possible, in order to avoid an assessment process being cut short as developers grow impatient. They may also deliver unwelcome messages for project developers and other energy sector stakeholders, such as a need to adjust expectations for power generation downwards if sensitive impacts are identified. It is therefore important to clearly communicate uncertainties, risks and liabilities from flow alterations, using non-technical language and conservative methodologies.

Even where projects are planned exclusively for power generation, if significant downstream impacts are to be expected, other stakeholders, such as sector agencies with relevant responsibilities and downstream jurisdictions, should not only be consulted, but invited to participate actively in the planning process. A steering committee can be formed – for example, with representatives of different agencies, jurisdictions and interest groups – to oversee the feasibility study and environmental and social impact assessment.

Participants may need assistance to understand the implications of different project options. Site visits and maps, such as of flood inundation areas, can help visualise such implications. Modelling support may allow participants to make proposals, and to test their feasibility and implications for various river uses.

Results of these evaluations in the preparation stage should be documented appropriately within the ESIA and ESMP, or other documents. They should be consistent with the hydrological, technical feasibility, and financial studies, and in particular, with design decisions and future operational plans. The respective licence and compliance obligations will be formulated by regulators, and should provide clarity on where and how flow commitments will be measured, and what might trigger an exception to these commitments or a review process for possible updates. Any owner/operator liability aspects of downstream releases also need to be documented. This information is then taken into account in the investment decision at the end of the preparation stage.

During the preparation stage, developers typically rely heavily on consultants for specialised studies. Financiers and contractors may provide additional contributions from their experience, if they are involved early enough in the preparation process.

3.1.3 Implementation

In the implementation stage, areas of focus are on river diversion and reservoir filling, as well as preparation of future flow deliveries. During construction, river diversion around the dam site usually has minor downstream impacts, as there is no upstream storage; and any quality impacts, such as increased turbidity, are temporary and can be mitigated through dedicated management measures such as sediment retention ponds.

Even though reservoir filling is also a temporary process, if not handled well, it can have major impacts downstream that generate opposition to the project. The impacts depend primarily on:

- the time required for filling, which depends on the **degree of regulation**, i.e. the relation between inflow and volume, which can range from hours to years (for example, Lake Volta in Ghana can store 4.28 years of average runoff in the Volta River);
- the timing of filling, during high or low flow periods;
- ongoing releases during filling, which may require the temporary use of diversion tunnels and other bottom outlets;
- whether filling is a one-time process or needs to be repeated (e.g. if the reservoir needs to be drawn down periodically for sediment flushing, or occasionally for repairs).

In some cases, a specific reservoir filling plan and associated commitments may be required. Responsibilities for decision-making must be clearly defined, as contractors and developers may push to fill the reservoir as rapidly as possible in order to commission the project.

During implementation, various measures relating to the future delivery of downstream flow commitments should be put in place, depending on the characteristics of the project. These generally include the physical release mechanisms and monitoring stations, and may incorporate measures as diverse as increased protection for cultural heritage sites, strengthening of bridge foundations, bank protection works, creation of artificial spawning habitats, multi-level pump locations for downstream abstractors, creation of off-river storages for farm water access and stock watering, or altered arrangements for downstream rafting company launch points.

As construction of a project takes several years, new issues may emerge over that time; new information about hydrological, social, environmental and power market conditions can be gathered, and plans for future downstream releases updated accordingly. At the end of the implementation period, the reservoir will be filled, and the project will be ready for commissioning.

3.1.4 Operations

Operational decisions about releases will be made by a combination of local, regional and headquarters staff of the hydropower company, and external agencies, which may include a different dam owner and power system dispatchers. The following steps should be taken with respect to downstream flow regimes:

- Monitor, document and compare flow releases and their consequences with those planned and predicted during the preparatory studies. There should be clarity regarding monitoring locations, their design, and responsibilities for their installation and maintenance among the owner/operator (most likely to be responsible for compliance monitoring) and public authorities (who will have a broader role in monitoring downstream changes and protecting downstream values).

- Include key pre-defined parameters regarding **hydrology** and **hydraulics** (e.g. flow rates and water levels), as well as hydropower generation, water quality, biota, morphology, and social and economic issues (including different water uses and public safety). Monitoring efforts should be commensurate with any identified risks or opportunities, as identified in the project preparation documents. Some parameters may be measured continuously, while others can be revisited on a less frequent basis (seasonally, annually, etc).

- Choose indicators for meeting downstream flow objectives that are practical, clearly attributable to project operations, and meaningful for stakeholders. Stakeholder mapping should have identified the most relevant downstream stakeholders who may have strong opinions on flow regimes. In developed countries in particular, dams are older on average (and their operational regimes may be seen as outdated), water resources policies and laws may be more progressive, and stakeholders may be better educated and able to advocate for better social and environmental outcomes. Under these circumstances, navigating stakeholder pressures on flow regimes may be key to maintaining a 'social licence to operate'.

- Analyse monitoring data for trends, and examine significant divergences from predictions to identify causes and effects. Parameters for monitoring may change over time, as some data series may be found to be less useful for analysis and other issues might emerge; however, to ensure continuity, they should only be changed with good justification.

- Based on monitoring and evaluation results, adjust releases as is feasible within constraints such as project design, licence conditions, and power purchase agreements. At longer time intervals, there may be opportunities for a systematic re-evaluation of operations and release commitments, in order to better respond to changes in economic, social and environmental conditions and objectives. These could be triggered, for example, by a major rehabilitation project, re-licensing, the listing of a species as endangered, the end of a power purchase agreement, the introduction of peak pricing, or a major flood. However, in mature hydropower plants that have been operating for many decades, a new downstream social and environmental equilibrium may have emerged, and the benefits of adjustments then have to be weighed against disruptions of the new equilibrium.

3.2 Criteria for good international industry practice

3.2.1 Assessment

Assessment includes all data collection and interpretation used to support downstream flow decisions, through all stages of a project. Data can include visual assessments and verbal feedback from stakeholders, which can be followed up with a focused quantitative survey and analysis.

This effort may be most intense and most important during the preparation of a project, when the baseline flow regime and potential altered flow regimes, and their effects throughout all affected river reaches, have to be analysed. This process continues during project implementation, when specific flow issues are identified and assessed.

During operations, ongoing or emerging issues are identified, and if specific management measures (such as minimum releases or controlled flood releases) are required, then monitoring must be undertaken to demonstrate compliance and to assess effectiveness. Older projects may have assessment requirements introduced based on changing water resources legislation, stakeholder expectations and pressures, or emerging cumulative impacts.

It is not enough to document that a particular flow has been released; in addition, the expected effects must be shown (e.g. meeting a water quality standard or maintaining a healthy population of an indicator species). Responsibilities for monitoring and evaluations for various questions of interest should be clearly allocated (e.g. among the owner/operator, government authorities, and other water users or polluters) and documented.

3.2.2 Management

Management involves addressing any significant issues identified through the assessment process in all stages of the project.

In the preparation stage, these issues are addressed by developing plans and processes for future downstream flow deliveries. These plans have to be comprehensive and include the flow objectives; the magnitude, range and variability of the flow regimes; the locations at which flows will be verified; and ongoing monitoring. They can be stand-alone plans that might be called 'Environmental Flow Management Plan' or 'Downstream Flow Release Plan', or can be integrated with other documents, as described above in Section 3.1.3.

Following modification of pre-project downstream flows, i.e. during the implementation and operation stages, downstream flow deliveries should address any identified issues, whether originally identified or emerging over time.

A good management plan provides for adaptive management: in other words, scenarios are defined, monitoring identifies if threshold conditions arise, and the plan specifies what kinds of responses are implemented under such scenarios.

Good practice also requires the public disclosure of any formal commitments, so that downstream stakeholders know what kinds of flow releases to expect and are able to form a view on how well these commitments are being met.

3.2.3 Stakeholder engagement

Stakeholder engagement is particularly relevant during project preparation. At appropriate times, downstream stakeholders need to be informed of the project's progress, in order to understand their interests in different aspects of flow releases, and give them an opportunity to provide feedback. There are often pre-existing differences in opinion or even conflicts between downstream stakeholders, which may be exacerbated by flow alterations.

During subsequent project stages, ongoing generic transparency, consultation and grievance mechanisms must be available for stakeholders regarding all issues, including downstream flows. Significant adjustments in operations (e.g. a shift towards peaking, to respond to new market opportunities), which result in downstream flows changes, should be subject to proactive stakeholder consultation.

3.2.4 Conformance/compliance

As mentioned above, in cases where a need to address downstream flow issues has been identified, legal and regulatory requirements such as licence and concession conditions and court decisions are likely to apply. Commitments to stakeholders (including, in some cases, to lenders) and internal plans by the operators will also apply. During project implementation and operation, developers, operators and supervising agencies need to verify that the project is in compliance and/or in conformance with these requirements, commitments and plans, or on track to become so.

Compliance and conformance are required of all parties with responsibility for a project, not only of the operator.

Compliance and conformance primarily imply that prescribed processes are followed (for example, a process to release an annual controlled flood). In some cases, the operator may also be responsible for a certain outcome of that process (for example, that the objectives of the controlled flood – such as encouraging seedling growth in a floodplain – are met). Because the outcome of the process can depend on many other variables beyond the control of the operator (for example, grazing pressure from animals of the floodplain), it is often not included under the operator's compliance obligations. Under an agreement with the project, another stakeholder (such as a farmer's group) may assume responsibility to control pressure (e.g. through fencing), and then needs to comply with the agreement. This compliance is equally part of the overall project's obligations, although it is not the operator's responsibility.

3.2.5 Outcomes

Outcomes are essentially the combined result of all activities described above, under Assessment, Management, Stakeholder Engagement, and Conformance/Compliance.

Before the project starts modifying flows, i.e. in the preparation stage, a good practice outcome is that planning for future downstream flows takes environmental, social and economic objectives, and where relevant, agreed transboundary objectives, into account.

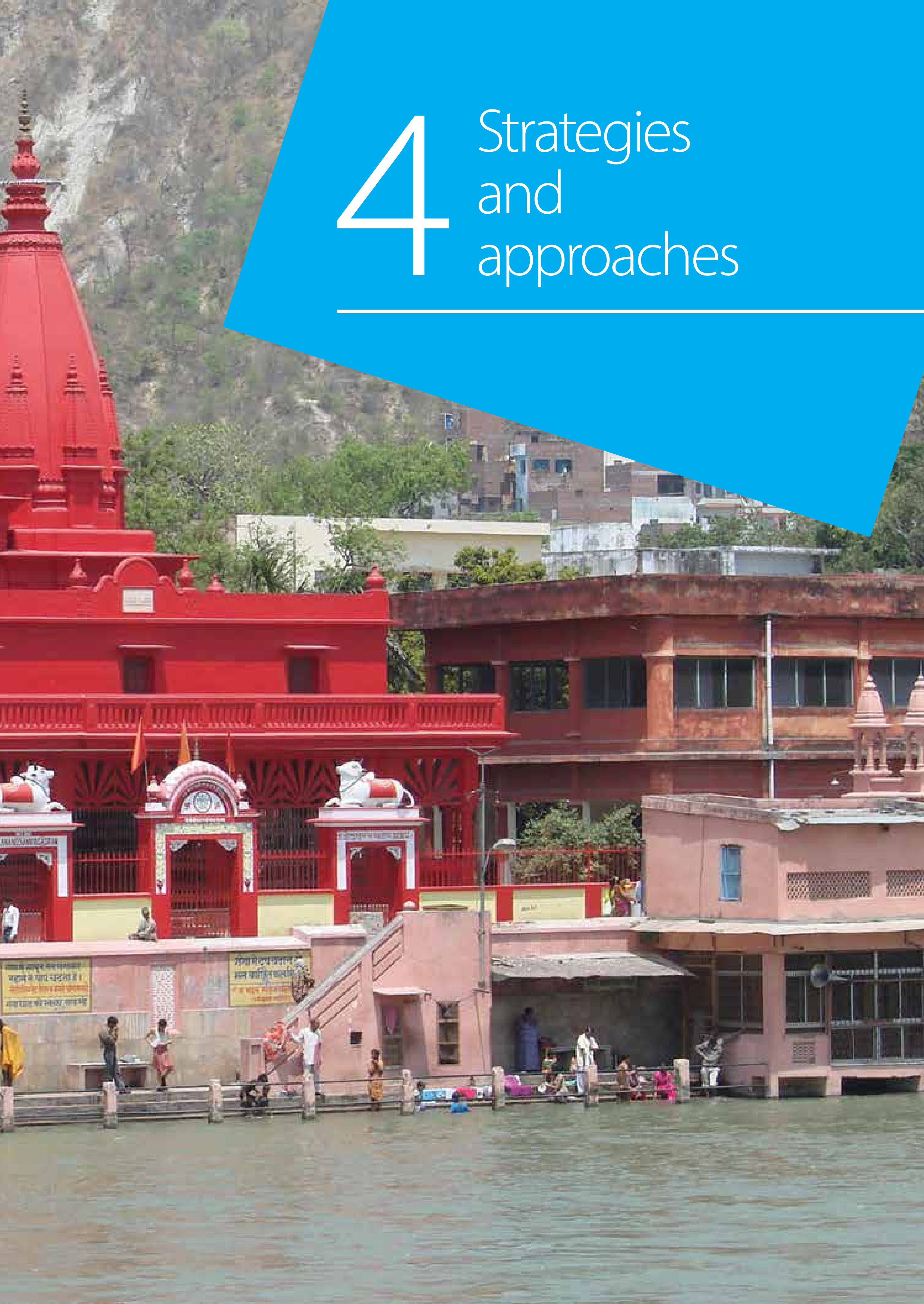
After the project starts modifying flows, i.e. in the implementation and operation stages, if important downstream issues have been identified and commitments to certain flow regimes have been made, a good practice outcome is again that these were informed by all relevant objectives.

Bholanath Sevashram temple in Haridwar on the Ganges River in India: the reservoir of the upstream Tehri project has a flood control capacity of 220 million m^3

Photo Credit: Joerg Hartmann

4

Strategies and approaches



Strategies and approaches

This chapter offers practical solutions to downstream flows issues. It starts with the highest-level approaches for avoidance and coordination, followed by project-level approaches to evaluate those impacts that cannot be avoided, and approaches to identify operational regimes that can be considered a good balance. Finally, it discusses a series of mitigation options and their requirements in terms of design and operations.

The planned Las Cruces project on the San Pedro Mezquital River in Mexico was suspended over downstream impact concerns, including on oyster aquaculture dependent on brackish water in the Marismas Nacionales wetlands
Photo Credit: Joerg Hartmann

4.1 Siting, design and operational choices at the basin level

The easiest downstream impacts to manage are those that can be avoided. Following the mitigation hierarchy, avoidance should be the first priority, before considering minimisation, mitigation and compensation measures. The main options for avoidance are related to choices at the basin level.

The first option is to screen all potential sites in a basin for downstream impacts, and to select sites with low sensitivity of downstream reaches. There may be heavily modified reaches where siting a hydropower project upstream makes little difference, or may even have – on balance – more positive impacts; for example, in the case of a regulating project directly upstream of a reach with large urban populations, heavy economic use, and is at risk from floods. There may also be sites available directly upstream of a large reservoir or a large tributary which can buffer any flow alterations. High-head run-of-river projects may also fall into this category if a diversion reach with relatively lower values can be identified (e.g. in a steep canyon, without human access and visibility, and with natural barriers such as waterfalls for fish migration, or located too high in the mountains to be a viable habitat for many aquatic species).

The second option is to choose sites which lend themselves to designs with minimal downstream impacts. As described above, low-head run-of-river projects on large lowland rivers, or closed-loop pumped storage projects, fall into this category.

Identifying such options is easier in countries with comprehensive hydropower development masterplans that not only identify potential sites, but also describe the characteristics of all relevant river reaches in a basin. Cumulative impact assessments or strategic environmental assessments may assist in identifying the lowest impact options.

More comprehensive basin-level approaches are often labelled as Integrated River Basin Management (IRBM) or Integrated Water Resource Management (IWRM). They have long been proposed as frameworks for more holistic approaches that would integrate resource management across different water-related sectors – instead of having each sector operate independently – and ensure that the various downstream impacts of any upstream decisions are taken into account. For example, investment and operational decisions of an upstream irrigation district would take impacts on downstream hydropower into consideration.

Integrated management should aim to resolve the sharing of costs and benefits of alternative siting, design and operational options among different entities. In principle, basin authorities could identify an overall optimal water allocation and either impose required releases on all operators, or provide incentives through fees, taxes, royalties or subsidies.

Although it is easy to recognise benefits for society from integrated management, it has proven difficult to create basin institutions that have actual authority over different water uses in a basin. Furthermore, integrated management is still rarely the basis for investment and operational decisions. The main world region with effective basin authorities and plans for integrated management appears to be the European Union, where the Water Framework Directive was implemented by member states in 2000, with a commitment to achieve good qualitative and quantitative status of all water bodies.

4.2 Assessment methods at the project level

There are many different methods for predicting the implications of flow regimes for different river uses, values and services, as well as methods to evaluate trade-offs and identify well-balanced flow regimes. Methods should be fit-for-purpose, i.e. neither unnecessarily complex, costly and time-consuming, nor overly simplistic.

For simplicity, here we first discuss methods to assess the impacts of flow releases on the primary objective of power generation, then methods to assess impacts on other objectives, and finally methods to compare and balance different objectives. This tiered approach is based on the types of studies typically undertaken in the industry.

In principle, a fully integrated downstream flows assessment framework for different objectives could be preferable, but most assessment purposes can be achieved within traditional study formats, as long as they are performed in an iterative and balanced manner, and their results are consistent with each other.

4.2.1 Generation assessments

The balancing of all downstream objectives must include the generation and revenue objectives of the hydropower operator.

During the preparation stage, planners study the power and energy potential of a project, in order to optimise the design for hydrological and market conditions, and to estimate future revenues. These studies may include simulations of reservoir operations based on historic flow series and sensitivity analyses; for example, to account for flows that change with climate or with upstream developments. Different storage capacities, turbine numbers and sizes, and other technical parameters are tested for their generation and revenue implications.

Through the same process, different constraints on releases (e.g. minimum releases, ramping rules or annual flushing flows) can be tested. This generally shows that fewer flow constraints on the hydropower project result in higher generation and revenues, but it is a partial assessment that does not yet take into account other costs and risks from negative downstream impacts.

The forecasting of inflows also plays an important role during subsequent project phases. During construction, it informs the scheduling of civil works and of reservoir filling. During operations, short-term (e.g. weather-based), seasonal, and annual (e.g. identification of El Niño and La Niña conditions) forecasting informs generation decisions. In a pure run-of-river project, the forecasting of inflows translates directly into generation forecasting. In a storage project, it is used for storage management under uncertainty.

For example, in regions with a flow regime dependent on snowmelt, the measurement of snowpack allows for a medium-term forecast. A large snowpack during winter will provide large inflows in the spring and summer. Releases for generation and/or for other downstream objectives during the winter can then be increased because it is highly likely that the reservoir will refill by summer.

4.2.2 Environmental flows assessments

4.2.2.1. Definition

An important downstream objective is to protect the environment through an adequate flow regime. Environmental flows have been defined in the Brisbane Declaration (2017 update) as "the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being". Environmental flow assessments, therefore, have to determine the required "quantity, timing, and quality" of flows.

These assessments should be a component of a project's ESIA for a particular geographical area impacted by a hydropower project, namely the downstream area. Like other components of an ESIA, environmental flows assessments should provide actionable advice on the mitigation of negative impacts (through the entire mitigation hierarchy) and the enhancement of positive impacts. To achieve this, they must be closely co-ordinated with other project activities in order to avoid inconsistencies, delays, and conflicts within the project team.

Originally, the concept of environmental flows was focused on river ecology, but the social and economic dimensions of flows are increasingly emphasised. Today, the scope of environmental flow assessments is strongly influenced by the concept of ecosystem services. An ecosystem is a community of living organisms in conjunction with the non-living components of their environment, interacting as a system. Following the categories of the Millennium Ecosystem Assessment, river ecosystems provide four types of ecosystem services; namely:

- provisioning (e.g. water for consumptive and non-consumptive uses, fish and other aquatic organisms, sand and gravel);
- regulating (e.g. flood regulation, erosion control, water purification);
- cultural (e.g. recreational, tourism, aesthetic, spiritual);
- supporting, which back up the production of all other services (e.g. primary production, nutrient cycling on floodplains, habitat for biodiversity).

Note that the above definition of environmental flows focuses on those social and economic uses of rivers that depend on aquatic ecosystems. For some uses, such as fishing, this appears obvious. However, the extent to which some other anthropogenic river uses – such as navigation, gravel extraction, or cooling of thermal power plants – depend on ecosystems and their biotic components is debatable. In this guide we cover all downstream social and economic river uses (other than hydropower generation, covered in its own Section 4.2.1) equally, irrespective of their dependence on living or non-living ecosystem components. This can be seen as a somewhat broader definition of environmental flows than the Brisbane Declaration.

Environmental flows have emerged as a broadly accepted concept in recent years. Some jurisdictions still use similar terminology such as 'ecological', 'compensation' or 'minimum' flows. However, even in these cases, the interpretation by regulators has often moved towards a consensus that includes socio-economic aspects and some variability in the flow regime. Also, developers can move beyond basic regulatory requirements and voluntarily commit to a more balanced flow regime.

4.2.2.2. Methodologies

Traditionally, four broad categories of environmental flow determination methodologies are distinguished. In order of increasing resolution/ sophistication, time and cost, these are: hydrological, **hydraulic rating**, habitat simulation and holistic methods. Table 1 shows the main characteristics of these four categories of methodologies. Other reviews, such as by the World Bank Group (2018), offer similar overviews.

Table 1 Environmental flow assessment methodologies[6]

	Ecosystem Attributes/ Components	Requirements
Hydrological	Whole ecosystem condition/ health, or nonspecific. Some include specific components (e.g. physical habitat, fish).	Primarily desktop, with low data needs. Use virgin/naturalised (or other reference state) historical flow records (daily, monthly or annual). Single flow indices (often low-flow metrics), or more commonly multiple ecologically relevant flow metrics characterising flow regime / whole hydrograph. Some use historical ecological data, hydraulic habitat data, or meta-analysis of results of multiple environmental water assessments to derive rule. Require expertise of a hydrologist. Few require ecological or geomorphological expertise, but such expertise is highly advantageous.
Hydraulic Rating	Aquatic (instream) physical habitat for target species or assemblages.	Low to moderate data needs. Desktop analysis and limited field surveys. Historical flow records. Discharge linked to hydraulic variables, typically single river cross-section/ transect. Single or multiple hydraulic variables. Require moderate expertise (hydrologist, field hydraulic habitat assessment, and modelling). Few require ecological or geomorphological expertise.
Habitat Simulation	Primarily instream physical habitat for target species, guilds or assemblages. Some also consider channel form, sediment transport, water quality, riparian vegetation, wildlife, recreation and aesthetics.	Moderate to high data needs. Desktop, and field surveys. Historical flow records, typically average daily discharge. Few to many hydraulic variables are modelled at a range of discharges at multiple river cross-sections. Physical habitat availability, utilisation, and preference data, or similar models, for target biota. A few use statistical summary methods based on results of multiple physical habitat studies.

Resource Intensity	Output	Appropriate Application
Low time and cost, and low or moderate technical capacity	Mostly simple, flow targets for maintaining river health, based on estimates of the percentage of annual, seasonal or monthly volume (often termed the minimum flow) that should be left in a river to maintain acceptable habitat or varying levels of river condition. Often expressed as percentage of monthly or annual flow (median or mean); or as limits to change in vital flow parameters, commonly low-flow indices. Low resolution, complexity, flexibility and confidence, or moderate and dynamic in a few more recent regime-focused methods.	Reconnaissance/planning level of water resource developments. Unsuitable for high-profile, negotiated cases, or where whole flow regime dynamics are critical. As a tool within habitat simulation or holistic methods. For highly data-deficient systems with limited ecological information. Regionalisation potential for different river ecotypes.
Mostly low, sometimes moderate time, cost and technical capacity	Hydraulic variables (e.g. wetted perimeter, depth) used as surrogate for habitat flow needs of target species or assemblages. Low, sometimes moderate, resolution, complexity, flexibility and confidence.	Water resource developments where little negotiation is involved. As a tool within habitat simulation or holistic methods.
High to sometimes moderate time, cost and technical capacity	Output in the form of weighted usable area (WUA) or similar habitat metrics for target biota (fish, invertebrates, plants). Often includes comparative analyses of time series of habitat availability, and duration and use. Moderate to high resolution, complexity and confidence, moderate flexibility.	Water resource developments, often large-scale, involving rivers of moderate to high strategic importance, often with complex, negotiated trade-offs among users. Commonly used as a method within holistic approaches and frameworks. Useful to examine a variety of alternative environmental water regime scenarios for several species/life stages/assemblages.

Holistic (ecosystem) methods and frameworks	Entire ecosystem, all or several ecological components. Most consider instream and riparian components, some also consider groundwater, wetlands, floodplains, deltas, estuaries, lagoons, coastal waters. Few consider geomorphic processes (e.g. sediment dynamics, channel adjustments), or ecological functions/processes (e.g. nutrient dynamics, food web structure). Several explicitly address social and economic (e.g. livelihoods of rural subsistence users, human health) dependencies on species, ecosystem resources, and processes (i.e. ecosystem services, e.g. fisheries).	Typically, moderate to high knowledge and expertise, but several used in data-poor contexts. Desktop and often field studies (seasonal or more intensive). Many reliant on a mix of data and expert judgment, using expert panels. Some use both scientific and traditional knowledge to develop or infer flow–ecology–social relationships. Use virgin/naturalised historical flow records, or rainfall records/ other data for ungauged sites. Several use hydraulic habitat variables from multiple cross- sections. Typically use biological data on flow–ecology relationships for lifecycle stages of aquatic and riparian species, assemblages and components (e.g. fish migration and spawning cues, riparian water quality tolerances, exotic species requirements). Range of experts from different disciplines, including ecologists, hydrologists, and often a geomorphologist. Several include social scientists, other specialists (e.g. water chemistry, health), water managers.

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6 Poff, Tharme and Arthington (2017). Table does not include regional and landscape-level holistic approaches, which are less relevant for environmental flow studies related to individual hydropower projects.

Moderate to high time, cost and technical capacity	Recommended hydrological regime linked to explicit quantitative or qualitative ecological, geomorphological, and sometimes, social and economic responses and consequences. Some address environmental water regimes for dry or wet years. Moderate to high complexity and confidence. Typically, high resolution and flexibility. Several with potential to generate outputs for multiple scenarios (past, future). Some explicitly address probabilities, interaction effects, risk, and/or uncertainty. A few incorporate climate change.	Water resource developments, typically large scale, involving rivers of high conservation and/or strategic importance, and/or with complex, negotiated trade-offs among stakeholders. Simpler approaches (e.g. expert panels) often used in basin contexts where flow–ecology knowledge is limited, and limited trade-offs exist among users, and/or time, resources and capacity constraints exist. Used in planning stage of new developments to protect high conservation values. Also used in highly modified or novel ecosystems, with a focus on flow regime to deliver specific restoration objectives, or to address socio-ecological values and services in novel ecosystems.

Good practice requires that these scientific approaches be embedded within interactive frameworks that are objective-oriented and involve systematic stakeholder engagement. Local stakeholders need to be consulted, not just because they will be impacted, but also because of their knowledge of the river and its characteristics under different flow conditions. Environmental flows assessments should produce practical results that are understandable for stakeholders, including hydropower operators. Elements of the flow regime need to be matched to identified objectives that reflect river uses, values, and services of importance to stakeholders.

The approach taken to establish the relationships between flows and objectives needs to be proportional to the significance of the flow changes, and to the sensitivity and value of the flow-dependent aspects of the downstream river system. Simple approaches will be sufficient for projects with minor risks and opportunities; for example, a downstream city that will experience only minor flow changes, or that is not particularly sensitive because it has strong flood and drought resilience. More complex approaches are required for projects with major risks and opportunities. The level of resolution is related to the 'resource intensity' shown in Table 1, and to the fact that methodologies can be used at coarser or finer levels of detail. The World Bank Group (2018) recommends the use of a decision tree to determine the required level of resolution (Figure 5).

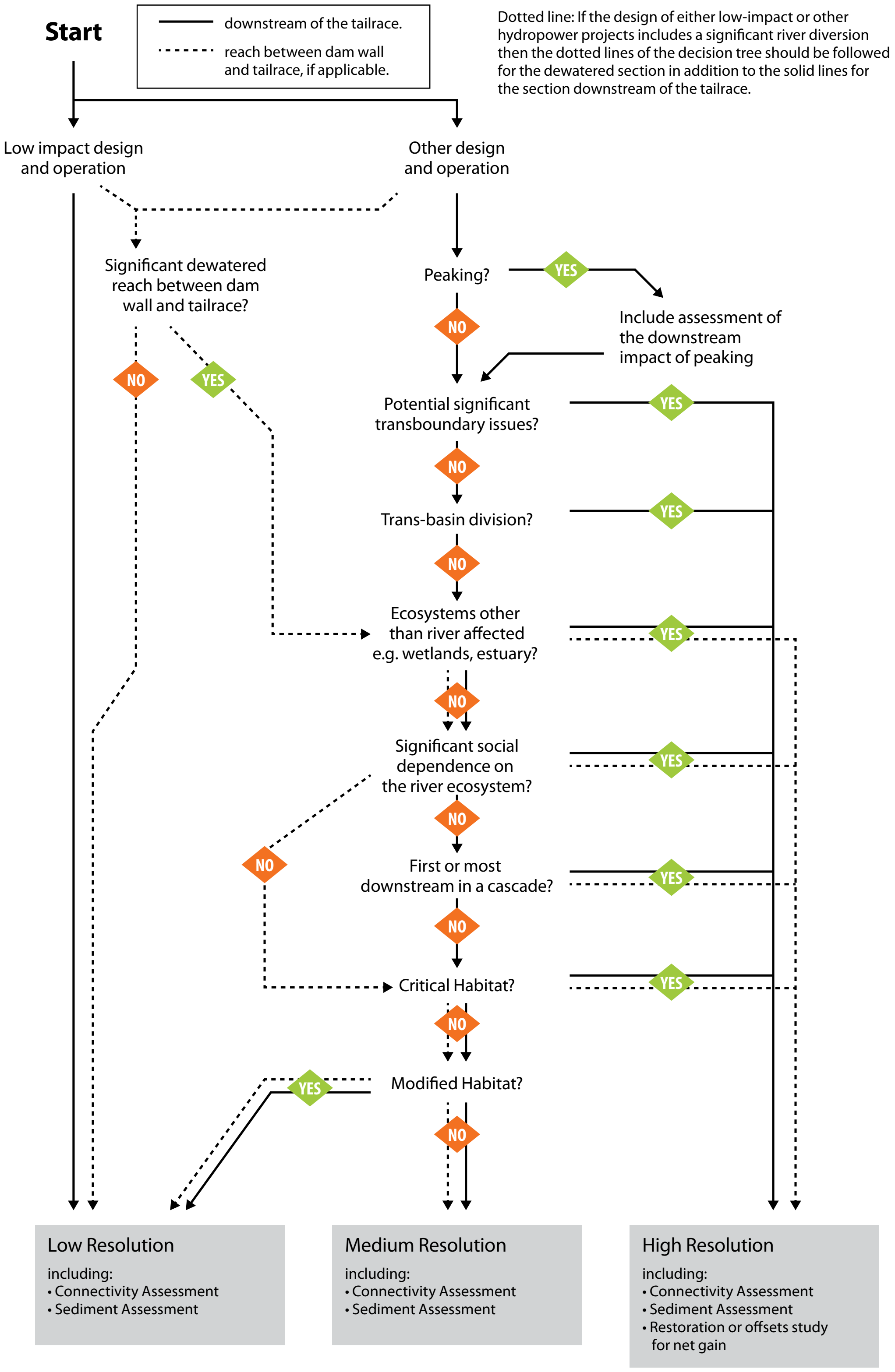

Figure 5. Decision tree for selecting environmental flows assessment method[7]

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[7] World Bank (2018)

4.2.2.3. Generic approach

Regardless of the exact approach chosen, good practice requires environmental flow assessments to be methodological and defensible in determining the link between flows and objectives, and to generally follow a logical 12-step framework with clear responsibilities for each step. The steps are grouped into four stages:

Stage A: Characterising the Downstream Flows and Associated Values

1. Review of available maps, aerial photos and satellite images of the river system, catchment areas, and major tributaries downstream of the project, in order to characterise the flow network and significant features (e.g. other water-use infrastructure, land uses, settlements, protected areas).

2. Review of climate, meteorological and hydrological data, to form a view regarding the major pre-project flow characteristics of the river.

3. Review of the storage and operational characteristics of the project, to identify the potential implications for downstream flows.

4. Definition of significant river reaches downstream of the project, from a hydrological perspective (e.g. between the dam, tailrace, major tributaries and major water abstraction points).

5. Identification of important river uses, values and services in each of the downstream reaches based on analysis of existing data, plus consultations with downstream communities and other stakeholders.

Stage B: Defining Project Impacts

6. Design and implementation of more focused data collection, in order to evaluate the sensitivity of existing uses, values and services to potential flow changes from the project, noting that these data may take several years to collect.

7. Analysis of pre-project and post-project relationships between flows and important uses, values and services for each affected reach; identification of the characteristics of the flow regime most relevant to maintaining those uses, values and services.

Stage C: Cost–Benefit Analysis of Impact Mitigation Options

8. Identification of mitigation options that could address impacts on uses, values and services, based on data analysis and consultations; options should follow the mitigation hierarchy (avoid, minimise, mitigate, compensate) and may include water management, infrastructure, or other management actions, including compensation options for significant residual downstream impacts that cannot be mitigated.

9. Cost–benefit analyses of mitigation and compensation options, including both the opportunity costs of foregone generation and the cash outlays for other options.

10. Discussions with stakeholders on priority approaches.

Stage D: Mitigation Commitments

11. Design of downstream flow commitments on a reach-impact basis (as described in Sections 4.3 and 4.4).

12. Definition of supplementary commitments, to address residual downstream impacts that are not resolved through flow management measures (as described in Section 4.5).

4.2.2.4. Examples

Most environmental flows assessments are undertaken during initial project preparation, and some to support project re-operation or re-licensing. Some assessments are also conducted independently of individual hydropower projects, from a water resource management or research perspective. These can be highly instructive, as they take the downstream river and its values as the departing point, rather than the operational requirements of an individual hydropower plant. For example, an assessment on the lower Zambezi River (Beilfuss and Brown, 2010) looked specifically at three elements of the flow regime (low season flows, annual floods, and 1:5-year return floods) that were strongly modified by the upstream dams. It found that most river uses, values and services would benefit from a flow regime closer to the historic natural regime. Higher annual flood flows would enhance the productivity of flood recession and river-bank agriculture for cash and food crops, estuarine and coastal ecology, freshwater fisheries, livestock and wildlife grazing grounds, and water bird productivity, as well as floodplain water supply (groundwater recharge).

Annex 2 shows some typical downstream flows changes, their environmental and social consequences, and mitigation measures in a number of projects evaluated using the Hydropower Assessment Sustainability Protocol (HSAP). These range from major flow alterations over long river reaches and downstream of multiple project components, such as Kaunertal in Austria and Kárahnjúkar in Iceland, to projects discharging directly into a downstream reservoir that buffers any impacts, such as Jirau in Brazil and Keeyask in Canada. Accordingly, the depth and breadth

Box 3: Assessment of Impacts on Downstream Sediment Transport

The operation of an upstream hydropower project can create major impacts on sediment-related downstream uses, values and services:

- Downstream of a reservoir with high trapping efficiency, sand miners may lose their livelihoods, and the construction industry a major source of raw materials. In the Nachtigal project in Cameroon, a livelihood restoration plan for the artisanal downstream sand extraction industry, which employs over 1,000 workers, is being implemented.

- Also downstream of a reservoir, a river 'starved of sediments' can erode its banks and bed, affecting riverbank residents and groundwater levels. The amount of erosion depends on flow release patterns: if flood peaks are curtailed, also the erosive power and the transport capacity of the river are reduced, and clogging may occur instead.

- Flushing of the reservoir or of clogged downstream reaches may create unnaturally high and sediment-laden releases at particular times of the year, thus impacting downstream river reaches and burdening downstream reservoirs with a sedimentation problem.

- In a diversion reach, as flows are reduced, the transport capacity of the river is diminished. This can lead to significant sediment accumulations if tributaries deposit major sediment loads, and then a lack of sediment further downstream. Controlled flood releases may be necessary to re-mobilise the accumulated sediment.

- In river channels filled with large amounts of sediment, minimum flow releases may travel at least partially underground, through the gravel and sand, and not be available as a surface flow.

- Sediment is an important element of habitats for many aquatic species, and changes in sediment transport will affect those habitats and species.

- Flow changes can make extraction of sand and gravel for construction purposes easier or more difficult, depending on how different reaches are affected. In reduced-flow reaches it may be improved, as the river is easier to access and may have more material available. In reaches below peaking plants, workers and equipment may be at risk from rapidly fluctuating releases. In reaches with increased baseflow below a regulating reservoir, formerly used sandbanks may no longer be accessible, as in the Lom Pangar project in Cameroon.

required for a good practice environmental flows assessment can vary significantly.

The potential complexities of environmental flows assessments can be illustrated by looking at just one issue, the impact of flow regimes on sediment transport (see also Section 2.3.9 and the How-to Guide on Sedimentation and Erosion, IHA 2019).

The example of sediment as described in Box 3 illustrates how diverse and site-specific the relationships between flow regimes and just one element of the downstream environment can be, and how challenging it can be to obtain a complete overview of downstream impacts. It can be a challenge even to merely optimise downstream flows for sediment-related objectives (through siting, design and operations), let alone for all objectives simultaneously. In practice, this means that the scoping of potential impacts and the determination of their significance are highly important steps.

4.2.3 Trade-off analysis

Typically, flow alterations will have mixed outcomes, with some values and stakeholders benefitting and others negatively affected. Informed decisions about flow regimes require an assessment of trade-offs. Decisions about trade-offs are a fact of daily life, and stakeholders will intuitively understand that there is generally no process and no solution that will perfectly satisfy everybody. Instead, the objective is an acceptable compromise between relevant values and stakeholders.

Figure 6. Trade-off between two objectives[8]

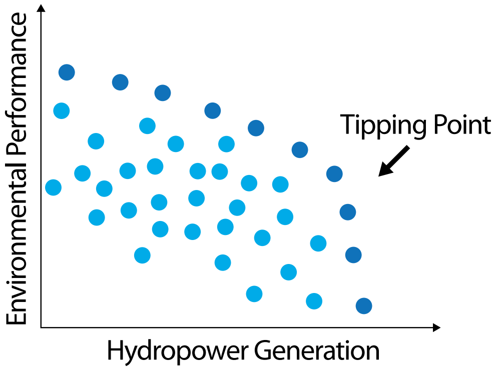

Figure 6 illustrates some typical features of a simple, ideal-type trade-off analysis with only two objectives:

- Every dot in the chart represents a downstream flow regime, as a result of design and operational decisions for the upstream hydropower plant.
- Every flow regime is associated with a certain environmental performance. Ideally, this performance can be quantified with indicators such as the abundance of a particular fish species, a water quality index, etc.
- Every flow regime is also associated with a certain outcome for hydropower generation, quantified as energy, firm energy, or revenue, for example.
- Only the dark blue dots are of interest to decision-makers. These solutions are called Pareto-optimal or Pareto-efficient, and together they form a Pareto frontier. The light blue dots are not of interest, because they can be improved in both dimensions, by moving towards the Pareto frontier.
- Along the Pareto frontier, a gain in one dimension (benefit) can only be made by accepting a loss in the other dimension (cost).
- Depending on the shape of the Pareto frontier, a gain in one dimension may result in very little loss in the other dimension, or may carry relatively large penalties. Tipping points in the curve may help identify areas where improvements are easier to achieve.

There are many methods for analysing trade-offs and making decisions when two or more objectives are involved, with varying degrees of formalisation and complexity. Trade-off or multi-criteria analysis generally has the advantage of making decisions more transparent and objective. It may also be possible to identify win-win situations, where the current practice is inferior for fulfilling several objectives, and a shift towards the Pareto frontier can benefit several stakeholders at the same time.

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[8] TNC, WWF, and the University of Manchester (2016)

While an awareness of trade-offs is always useful, in practice there are likely to be some limitations to relying on trade-off analysis to determine downstream flow regimes:

- The different objectives to be reconciled involve subjective human values and interests. The weight given to different criteria may depend on the influence of different stakeholder groups, and their ability to arrive at an acceptable compromise may depend on the level of social conflicts. Compromising is a social process which can only be informed, but may not be replaced by formal analysis. Relevant authorities that have to approve a flow regime may also have their own political objectives.

- There are technical challenges to formal analysis, including criteria that are not easily quantified, a potentially large number of criteria, and the dynamic and uncertain nature of the underlying hydrology.

Given these limitations, trade-off analysis is often used to evaluate more limited, specific changes in the flow regime, rather than the entire range of possible flow regimes. For example, initially a limited number of minimum flow levels could be compared with each other by looking at the implications for various criteria, such as fish habitats and hydropower generation. At the Trevallyn project in Tasmania, through an iterative process over years, minimum flow releases were increased first from 0.43 m^3/s to 1.5 m^3/s, and then to 2.5 m^3/s; furthermore, higher periodic releases for kayaking were introduced, based on studies and stakeholder surveys regarding threatened snails, fish and flora, visual amenities, recreation and water quality. This type of analysis can then be expanded to include more complex scenarios, such as those with seasonal flow variations.

At the good practice level, the Hydropower Sustainability Tools require that different flow objectives are assessed and taken into account. No specific methods are required, but by implication, the methods have to be commensurate to the problem. For example, an economic analysis of the costs of environmental flow constraints is appropriate where the value of generation is high, and if the reduction of generation is expected to be significant.

At the best practice level, the tools require that downstream flow plans represent an 'optimal fit' between different objectives. Optimal fit does not imply optimisation in a technical sense, i.e. a planning process where different criteria share a common unit of measurement (typically a monetary value). In principle, as different operational releases result in different monetary values for hydropower revenues, value of fish catch, and flood damages, the release level with the overall highest value could be seen as the optimal release level. The

Box 4: Assessment of the Costs of Flow Mitigation

A number of studies have been undertaken to establish the economic trade-offs of environmental flow constraints, either at the individual plant level or for a whole set of projects. In the US, the periodic relicensing process for privately owned hydropower plants often results in flow regime changes, such as shifting to a run-of-river mode of operations, for various reasons.

Of the 223 projects that were relicensed between 1988 and 2000, about 15 per cent of licences were changed in this way because of fish populations, aesthetics, maintaining constant reservoir levels for recreation, water quality, and erosion mitigation. A majority of changed projects had reduced peak releases after relicensing, while some actually had stronger diurnal fluctuations, resulting from upstream storage plant operations. The average reduction in generation efficiency was -3.5 per cent, but average numbers can obscure the wide range of outcomes. The implications of such licence changes were highly case-specific. In other words, the trade-off in terms of generation loss that is required to achieve a certain gain in objectives other than generation, is very different from case to case. Where the trade-off is large, it is worthwhile to analyse whether the non-generation objective can be achieved through other measures (for example, a re-regulating pond).

main difficulty of optimising in a downstream flows context is the monetary valuation of many of the relevant criteria.

Despite this difficulty, in some situations, optimisation may be possible and useful. A growing body of hydro-economic modelling aims to support water resource decisions, and specifically, the allocation of scarce water to different uses and users. Both the investment in new water infrastructure and its operation can be simulated and optimised over time using hydrological time series. Where the costs of supplying water (e.g. the costs of constructing storage reservoirs) as well as the value of and demand for water from different downstream users (e.g. hydropower operators and irrigation farmers) can be determined, hydro-economic models can provide insights for flow regime decisions.

Finally, an acceptable compromise does not imply that all objectives are given equal weight. Instead, a reasonable process must be in place to consider all of them and aim for an acceptable balance among them. This process may well result in one objective dominating the others. In the simple two-objective example in Figure 6, this would be represented by a 'corner solution'. For example, the affected downstream reach may be only a short distance between two reservoirs in a cascade, with few identifiable social or environmental values. In such a situation, a downstream flow regime that exclusively aims at maximising revenue could be considered a justifiable outcome. Conversely, there may be situations where downstream values are so high and sensitive that no flow alteration is allowed. In most settings, however, these 'corner solutions' would not be acceptable, and an intermediate solution would be selected.

The assessment methods discussed in Sections 4.1 and 4.2 will result in a preferred downstream flow regime, which then needs to be implemented through design and operational steps. These are described in the following Sections 4.3 and 4.4. If any improvements to that regime are identified, whether during an iterative preparation process or during operations as part of adaptive management, these also need to be implemented. The rationale for such changes needs to be clearly communicated, as some internal and external stakeholders may be reluctant to accept the costs or delays associated with changes.

4.3 Design requirements

4.3.1 Storage capacity

Reservoir planning and management is a separate sustainability topic, with its own requirements and guidance in the Hydropower Sustainability Tools. Most reservoirs are built to balance inflows and outflows over time. There are various methods for sizing a reservoir, generally with the objective of ensuring that cumulative outflows (determined by the downstream demand for water) can always, or with a certain probability, be met (or exceeded) by cumulative inflows.

The larger the active storage or degree of regulation, the more capacity a hydropower project has to control and alter downstream flows, compared to the pre-project situation. An operator may initially choose to not actively control downstream flows by operating in a run-of-river mode. However, by doing so, any positive downstream effects from flow alteration (e.g. stable baseload generation or flood control) are also foregone. Adaptive management may eventually lead to more active use of storage. Therefore, downstream impacts must always be included in reservoir planning and explored using modelling techniques.

4.3.2 Outlet locations and capacity

To release downstream flows at different times, dams and weirs associated with hydropower projects have various outlet structures, such as spillways, tailrace tunnels, weirs and bottom outlets. Some of these are controlled by valves and gates, while others – for example, ungated spillways and weirs – automatically start releasing when water reaches a certain level. In some cases, a dedicated turbine can be installed to generate electricity from downstream flow releases even if these are outside the efficient operating range of the main power station turbines, or to utilise minimum flow releases in the diversion reach between the dam and the powerhouse.

Ideally, an operator would have the ability to release a wide range of water volumes, from various reservoir depths, in a controlled manner. However, for technical and cost reasons, this is not always possible. Some of the typical limitations and their consequences are as follows:

- Almost all outlets (except for diversion weirs, which can simply be overflown) have a limited capacity to release water. Limits may also be imposed because of erosion risks directly below outflow structures, which may even include dam failure risks. This can be a constraint on high flow releases, such as controlled flood pulses.

- Bottom outlets can be useful 1) during reservoir filling, to guarantee continuous releases before the water in the reservoir reaches the level of the main intake; 2) to release sediment-rich water to maintain sediment transport; and 3) to empty the reservoir in emergencies or for repairs. However, bottom outlets are not always provided, and even where they exist, may not be operated frequently due to concern over operational problems, particularly in deep reservoirs.

- Ungated, fixed-diameter outlets and intakes, while guaranteeing a permanent release of minimum flows, do not allow variations or adaptive management.

- Intakes may be located relatively high in a reservoir, for example to draw water with low turbidity. However, they then may not be operated when drought conditions reduce water levels.

- Intakes located at a fixed level may correspond to a particular layer in a thermally stratified reservoir. That layer may not have the temperature or gas saturation desired for downstream releases, at least during part of the year. Flexible intake towers can draw water from different layers, but are relatively rare.

It is thus important to take any current and potential future requirements for releases into account during the initial design. Changing the design of outlets after commissioning is almost always associated with higher costs, but it may become more feasible during a major rehabilitation project.

4.3.3 Monitoring installations

Basic parameters such as downstream flows and water levels should be monitored over time, to allow analysis of trends and inform operational decisions.

The design, construction and installation of flow-gauging structures is a specialist endeavour which, to be cost-effective, should be undertaken with long-term monitoring requirements in mind. Monitoring stations should be located directly downstream of, as well as at reasonable distances from, project infrastructure where downstream flow changes have been predicted. The location directly downstream is typically for monitoring compliance. The operator is ultimately responsible for ensuring that all monitoring equipment is in place and is correctly operated, although in some jurisdictions public agencies may assume monitoring functions.

Depending on the types of predicted and managed impacts, various other indicators (temperature, turbidity, oxygen content, biological, geomorphological, socio-economic, etc.) may also be tracked over time. Some of these may have to be tracked manually, or collected periodically and sent to laboratories for analysis. However, water quantity and quality parameters can increasingly be monitored through automated data loggers, some of which can operate continuously and transmit data to control centres.

Hydrometric networks can be vital for multiple interests in river basins; their design, installation and operation should be undertaken in collaboration with public agencies. Data should be shared publicly, or at least be made available to water resources agencies and key downstream stakeholders, such as reservoir operators and major river users.

To separate downstream changes caused by a hydropower project from those caused by other factors (e.g. climate or land use), it may be useful to monitor conditions at control sites which are not influenced by the project, such as upstream of a reservoir. It is in the interest of project operators to monitor and document downstream conditions, to avoid being held liable for external changes.

4.4 Operational requirements

4.4.1 Water rights and water quality limits

Hydropower operators have to manage releases within the constraints imposed by licences and permits. In many countries, the main water resource management instruments are permits for abstractions from and for discharges into water bodies. Permits are granted and supervised by different types of authorities at various levels of jurisdiction, from basin to federal level.

While these instruments are effective for most water uses, they can falter in effectively and directly influencing water management by hydropower projects. Permits can be a formality without any constraints because hydropower is considered a priority user. In some cases, projects are exempt from requirements for water use permits because they are considered 'non-consumptive' users that do not abstract water from the river channel (even though evaporative losses from reservoir surfaces are sometimes larger than abstractions by other users). Changes in flow timing are difficult to regulate with water use permits, which often only consider maximum or total water volumes. In terms of water quality, the changes in turbidity, temperature, gas content, and other parameters that occur in reservoirs, are not always easily comparable to the municipal and industrial pollution problems for which water quality regulations were originally designed.

Nevertheless, where water quantity and quality permits apply, they may impose some direct constraints on downstream releases. Operators may also be indirectly constrained, in that they are not allowed to interfere with permits held by downstream river users, as discussed below.

4.4.2 Licensing conditions

Instead of using generic regulatory instruments for water resources, such as abstraction permits, most countries rely on their project licensing systems. Licensing can impose constraints on the original siting, design and operational choices. In some cases, licences are time-bound (for private projects in the US, for example, typically for 30 to 50 years), and adjustments to flow regimes can be made in the re-licensing process or when concessions expire. In other cases, licences impose monitoring of downstream impacts and adaptive management of operations.

A simple licensing regime imposes standard rules on all projects – for example, that the minimum release is never less than 10 per cent of the historic minimum flow. A more complex licensing regime formulates rules that take specific conditions downstream of a site into account, and may include seasonal variations of minimum flows, maximum releases, ramp-up and ramp-down rates, and sediment flushing provisions. It may also determine how flows are released, e.g. through bottom outlets, fixed or variable-level intakes, or over spillways and weirs. Generally, there appears to be a trend towards more complex rules over shorter periods of time.

Site-specific licensing rules require more capacity from regulators and other stakeholders, but are not necessarily more onerous for operators. For example, rules may be formulated as ranges rather than specific numbers, leaving some operational flexibility. In a cascade, only the last project downstream may be required to re-regulate flows to a more natural pattern, while the intermediate projects can operate with few constraints. The more pragmatic and cost-effective these rules are, while reducing environmental and social risks and thus ensuring public acceptance, the more likely it is that they will be accepted by hydropower investors and operators.

Licences should address impacts identified in a project ESIA (and in other documents) at the river basin level (such as navigation, irrigation, flood control and water supply plans), and implement the avoidance, mitigation and compensation actions defined in an ESMP. Licence conditions should be based on the identification of the relevant downstream reach, the primary impacts (physical flow changes), and secondary impacts (economic, social and environmental implications). Cumulative impacts with other facilities that influence the same reach should also be considered. Clear responsibilities for mitigation and compensation measures, in terms of implementation, timing, cost coverage, monitoring and evaluation, should be defined. The same rules and responsibilities also need to be reflected in contracts, such as concession agreements or power purchase agreements.

In practice, local impacts in the reservoir and works areas usually receive more regulatory attention than downstream impacts, and are more comprehensively addressed in licences. National and provincial authorities often issue licences with little awareness of and interest in downstream impacts. There may also be little continuing oversight of downstream conditions; and even if impacts are identified over time, they may not be easily attributable to individual projects, and may not lead to changes in licence conditions. A lack of regulatory capacity, however, does not exonerate operators from their responsibility to achieve good practices.

4.4.3 Operational rules

Most reservoirs are operated according to rule curves, established at the planning stage to provide long-term operation guidelines for reservoir managers. Rule curves often prescribe target reservoir volumes or levels throughout the year, as a relatively simple model that reservoir managers, stakeholders and the general public can easily understand. If reservoir levels are above a target range or level, downstream flow releases are increased; if they are below a target range or level, releases are curtailed.

Within the boundaries of rule curves, hydropower reservoirs are often more actively managed. Water availability – including expected inflows, based on medium- and short-term forecasts – is reported to operations planners and dispatchers. Operational and regulatory constraints such as intake capacities, minimum releases and maximum ramp rates are then taken into account when planning operations.

Because operations planners and dispatchers work at the level of the entire basin or grid, they may be able to identify operational options at that level which will reduce negative downstream impacts. For example, if a certain ramp-up of generation is required, it may be distributed across several hydropower power plants, thus minimising the flow increase downstream of any one plant. Or, by considering an array of reservoirs with flood control functions, coordinated operations may achieve a higher level of flood mitigation than a single reservoir.

The optimisation of reservoir operations and release decisions over time can be a highly complex mathematical modelling problem. While such models may be overly complicated for most operators and stakeholders, with technical support from specialised service providers they can help test and improve operational rules in an iterative manner, and inform discussions and negotiations among affected parties.

4.5 Mitigation and compensation for residual downstream impacts

In most cases, some residual negative impacts will remain,

- even after choosing low-impact sites and adjusting the design and operations; and/or
- because it is more feasible or cost-effective to deal with residual impacts through other measures, rather than by making adjustments to project siting, design and operations.

Table 2 provides examples of residual impacts and how to deal with them. In general, direct or targeted management measures can be categorised into those that reduce a residual impact, compensate stakeholders in kind, or compensate stakeholders financially. Financial compensation gives recipients the greatest degree of freedom over how to prioritise the use of funds, but also carries the risk that some downstream issues will remain unresolved if they are not prioritised by recipients. In general, measures should be chosen on the basis of their effectiveness and efficiency. The table is illustrative rather than comprehensive, due to the highly site-specific nature of downstream issues.

Additionally, providing indirect, completely non-targeted compensation measures is an option to complement more targeted measures. Downstream communities can be included in benefit-sharing

Table 2 Examples of residual impacts and management measures that are not flow-based

Residual Downstream Impact	Mitigation Option	In-Kind Compensation Option	Monetary Compensation Option
Reduced flow in a bypass reach, leading to water access problems for livestock	Improvement of water intakes	Provision of alternative water supplies, e.g. off-stream watering areas for stock	Purchase of water rights
Bank erosion	Bank protection works	Replacement of riverbank gardens lost to erosion, by new farmland	Purchase of riverbank land
Fish stock decline	Fish hatcheries; habitat restoration; artificial spawning areas	Support for aquaculture ponds or animal husbandry, to replace lost protein	Compensation payments to fishing communities
Degradation of a protected floodplain wetland area, and loss of biodiversity	Physical works to maintain wetland (e.g. channel dredging)	Creation of artificial wetlands to offset impacts	Financial contribution to national protected area system for land purchases or other protection measures
Water quality issues due to reduced dilution	Construction of wastewater treatment plant	Provision of alternative water supplies	General funding for water and sanitation investments prioritised by local communities
Public safety risks due to peaking operations	Re-regulation storage; alarm systems, warning signs and security fencing	Access paths and boat ramps to enable recreation on a different river stretch	General funding for recreation investments prioritised by local communities

schemes (e.g. through municipal budgets, equity participation, or infrastructure investments), which allow them to adapt more easily and rapidly to changed conditions. These options are discussed in the How-to Guide on Benefit Sharing, IHA (2019).

Mitigation and compensation costs do not necessarily have to be borne by a hydropower operator. For example, where water pollution is caused by an upstream source and was previously accepted because it was sufficiently diluted, the polluter may now be called upon to invest in wastewater treatment. Habitat restoration and improvement projects that seek to introduce more diversity and complexity into the downstream environment, may be undertaken jointly with other river users and government agencies.

Management measures may be voluntarily implemented by hydropower operators in order to increase community acceptance and reduce political and legal liabilities, even if they are not required under a regulatory framework. In some cases, operators could be brought to court, found liable for downstream damages, and required to mitigate and compensate for downstream impacts, especially where negligence or non-compliance is established.

4.6 Negotiated agreements with downstream stakeholders

In many cases, downstream communities could be positively affected by reservoir operations, for example through flood management and the augmentation of low flows in the dry season. Operators could also have opportunities to reduce negative downstream impacts. However, enhancements of positive impacts or reductions of negative impacts could require operational measures that are neither in the direct interest of the hydropower operator, nor required by the regulatory framework. In the absence of regulatory requirements, the question arises of whether and how operators can be induced to release a certain flow regime, in the interest of downstream stakeholders.

Conversely, an upstream operator may be constrained in their operations through a regulatory framework that protects downstream interests. This raises the question of whether and how downstream stakeholders can be induced to accept some damages.

These two situations represent two different legal scenarios: either the upstream hydropower plant has the right to release flows as is best for them, irrespective of impacts this imposes on downstream river users; or, downstream stakeholders have the right to not have any negative impacts imposed upon them. Agreeing on modifications of these rights through public sector planning and permitting processes can be difficult. Voluntary negotiated solutions – perhaps with the help of arbitration – may be a viable alternative in some cases. Ideally, these would take place within a robust legal framework that allows enforcement of contractual agreements.

In both scenarios, the parties could negotiate compensation payments. The distributional outcomes would be different depending on who holds the rights. In the first case, the hydropower operator would receive a payment to modify their releases; this payment would have to be enough to at least compensate for the loss in generation. In the second case, which is equivalent to the 'polluter pays' principle, the downstream stakeholders would receive a payment to accept an impact; this payment would have to be enough to at least compensate for their losses. The hydropower operator would have an incentive to keep this payment as low as possible, and would thus try to operate the dam in a way that minimises downstream impacts.

Irrespective of the initial distribution of rights in both cases, intermediate solutions might be found, and the outcomes could actually be quite close to each other. For example, the dam operator and a downstream navigation authority could agree that an annual controlled flood is released to flush sediment from the river channel and make dredging unnecessary. A dam operator and a downstream flood control agency could agree that the flood storage space in the reservoir is increased in advance of the wet season, which may be cheaper than raising embankment dykes downstream. A dam operator and a fishing cooperative could agree to suspend peaking operations during the spawning season, as this may be preferable to maintaining fish stocks through hatcheries.

Such negotiated solutions are more likely in developed countries with older operating projects, than in emerging economies where most new projects are located. They have not been tested in many countries, and can be difficult to achieve with multiple upstream and multiple downstream parties. However, a case can be made to create frameworks that would allow more such voluntary negotiations. This could increase the transparency of costs and benefits of different operations, and make it easier to find win-win solutions.

Such transactions would also allow changes to existing projects where regulators may have no legal basis for demanding changes after the granting of the initial licence, even if conditions change. Licences that are not time-bound may initially seem necessary to attract investors, but they carry a risk that licence conditions will become outdated over time. Changes in climate, land use, demand for water services downstream, power markets, and other factors are bound to make initial operating rules obsolete over time. Renewed consultations or market transactions may lead to adaptive solutions.

4.7 Transboundary agreements

Positive or negative downstream impacts on ecosystems and people across political borders present special challenges. Even within federal states, such as India, individual state governments focus on their own interests, and downstream states' regulatory authority does not extend to upstream states' projects. Hydropower development in India's north-east has been delayed by disagreements among states over downstream impacts. Across international borders, countries are concerned about their upstream neighbours' ability to change flow patterns. For instance, Kyrgyzstan depends on the Toktogul dam for most of its power, while downstream Uzbekistan and Kazakhstan depend on its releases for much of their irrigation. Vietnam is concerned that hydropower development by its upstream neighbours will cause major changes to Mekong River flows and affect the delta, its most productive agricultural area.

In such cases, direct political agreements are sought between provinces, states and countries to regulate downstream impacts. Even merely the exchange of information about hydrological data and dam releases can improve operations and build trust between up- and downstream countries. On the Indus River, a treaty between Pakistan and India has been remarkably stable despite political tensions. Some countries have also agreed to coordinate on the basis of an international regime, such as the UN's 1997 Convention on the Non-navigational Uses of International Watercourses; however, not many upstream countries have ratified this convention.

Reaching agreements on a case-by-case basis may be a way forward, although this is certainly easier when countries share a common vision and a long tradition of good-faith dialogue. One example of a cross-border agreement that was able to provide balanced outcomes is the re-licensing of the Kembs plant, which is owned by EDF. Here, authorities and stakeholders from France, Germany and Switzerland successfully cooperated to improve downstream flows regimes and other environmental aspects along a 50-km bypass reach on the Rhine.

Some lenders, such as the World Bank, require notification of other riparian countries in the case of projects on transboundary rivers, and are only willing to fund a project if the interests of other riparians are not affected, an agreement with other riparians is in place, a non-objection is received from these riparians, or an objection is received but found to be without merit.

4.8 Adaptive management

During the operations stage, monitoring, evaluation and adjustments are the key tasks regarding downstream flow regimes (as described in Section 3.1.4 above). Section 4.3.3 elaborated on requirements for monitoring equipment.

Power generation requirements, hydrology, downstream impacts, and downstream stakeholders' interests are all difficult to accurately predict, and are bound to evolve over time. Even if they are initially well-balanced, downstream release rules are likely to benefit from adjustments as these conditions evolve.

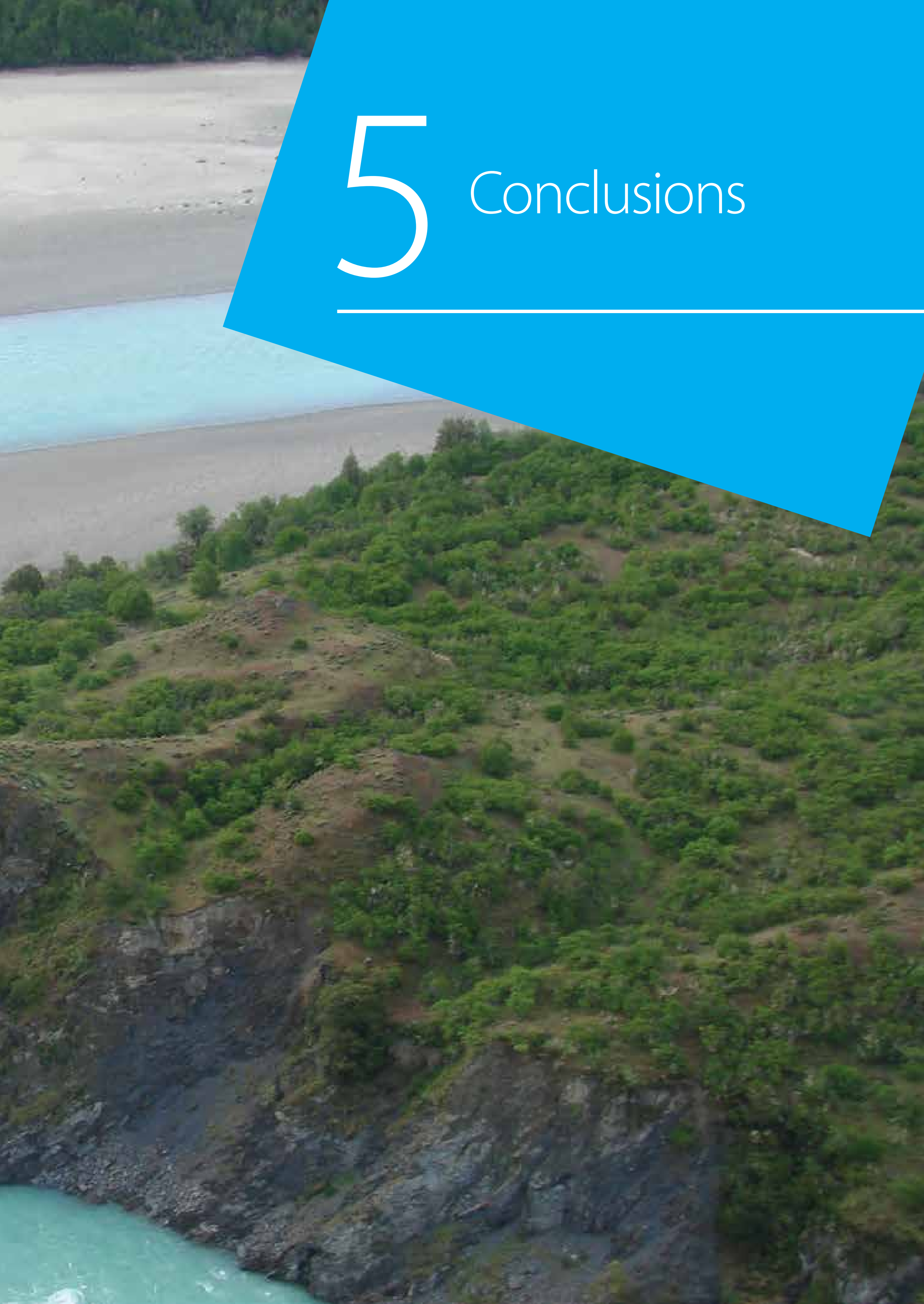
There may be limits to adaptation, at least in the short term, due to technical constraints (e.g. size of valves or pipes), regulatory constraints (e.g. licence conditions) and commercial constraints (e.g. delivery obligations in PPAs). Some of these limits can be overcome with time. Ongoing communication, consultation and cooperation among stakeholders – such as hydropower operators, regulatory agencies, dispatchers, and downstream water users and communities – are generally necessary if they are to agree on adjustments to flow regimes.

Where adjustments can be made relatively easily, and the downstream environment is not particularly sensitive and responds quickly to operational changes, a 'trial-and-error' approach to downstream flows may be feasible. This would adopt reasonable design and operational features, test their downstream impacts, and adjust them in a stepwise manner until no further substantial improvements appear possible.

Natural sediment transport on the unregulated Baker River in Chile
Photo Credit: Joerg Hartmann

5

Conclusions



Conclusions

Making sound decisions about downstream releases requires reliable information, as well as mechanisms to reconcile different interests. As discussed in previous chapters, although various approaches are being applied to this issue, the outcomes are not always satisfactory. This guide has presented some principles that can be followed to achieve balanced, broadly acceptable solutions for downstream flows:

- Downstream impacts should be recognised as potentially important project impacts, even if some developers have limited experience with the assessment and management of these impacts, and their scale and diversity can initially seem daunting.
- Voluntary, consultative and negotiated approaches should be considered alongside compliance with regulatory requirements.

Fishing below the Sogamoso project in Colombia
Photo credit: Joerg Hartmann

- Early in project preparation, planners should obtain information on current and expected future downstream river uses, users and values, and how they will be affected by different siting, design and operational alternatives.
- After choosing siting, design, and operational features with a view towards avoiding and reducing negative and enhancing positive downstream impacts, any residual negative impacts should be mitigated and compensated for, as much as is reasonably possible.
- Economic, social and environmental downstream flow objectives should be considered as equally legitimate, and balanced outcomes should be pursued. This does not imply that these objectives have equal weight in all cases.
- Downstream flow releases should be set pragmatically and be managed adaptively over time.

Annex 1

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Annex 2

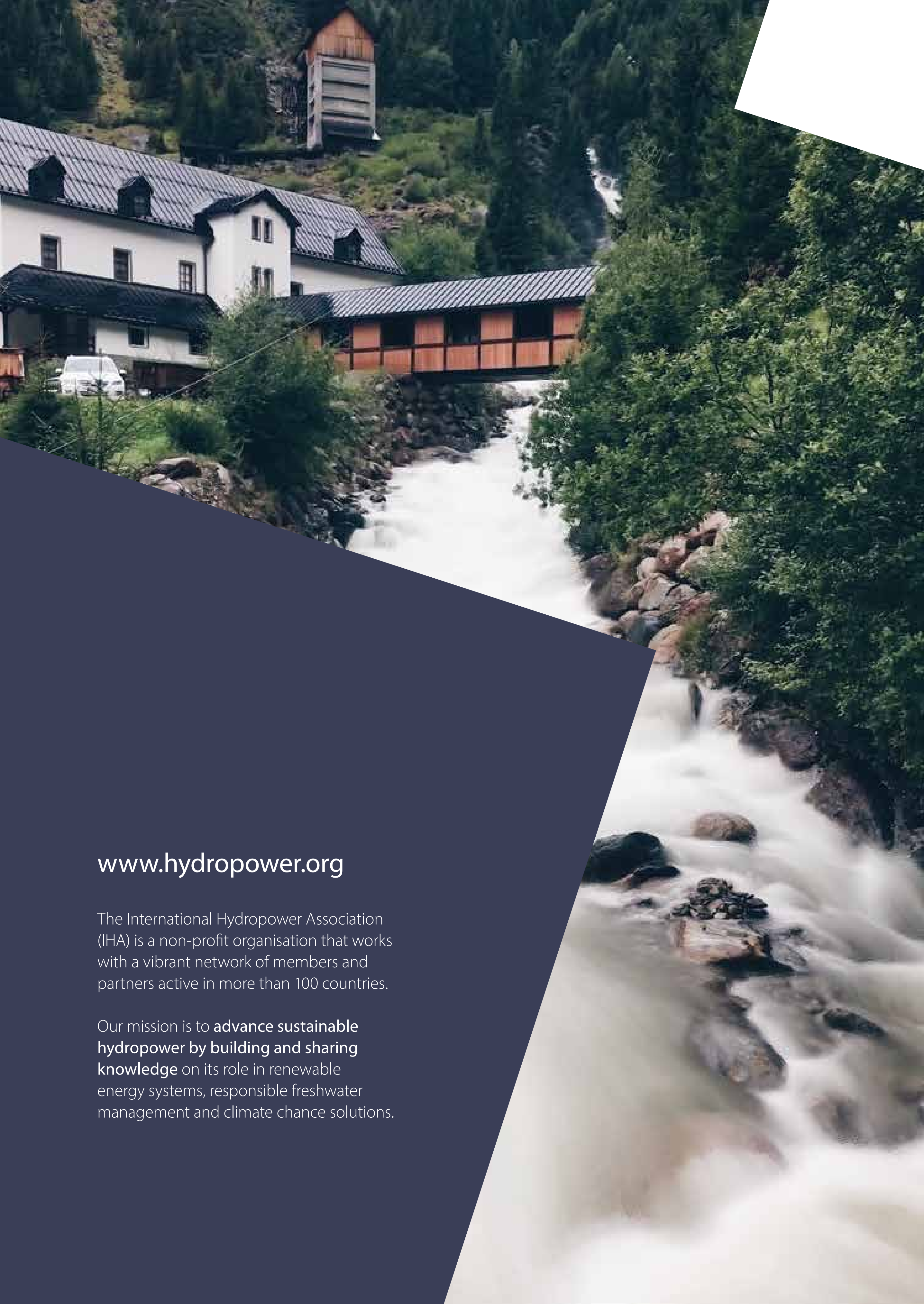
Project examples

From assessments using the Hydropower Sustainability Assessment Protocol

Project	Downstream Flow Issues	Management Measures
Blanda, 150 MW **Operation stage** **Iceland**	Bypass reach (~20 km) with no releases from dam, only inflows from tributaries Downstream of power station: reduced seasonal variability, increased short-term variations Impacts on valuable salmon fishery	Minimum release from power station Ramp-up/down rules
Devoll, 256 MW **Implementation stage** **Albania**	Reduced flows during reservoir filling Bypass reach (12 km): reduced flow Seasonal regulation, but larger short-term variations Impacts on biodiversity, flood protection and dilution of pollution.	Minimum releases from dams
Hvammur, 82 MW **Preparation stage** **Iceland**	Bypass reach (3 km) with reduced flow Affected salmon habitat Reduced groundwater level, with impacts on riparian vegetation.	Minimum release from dam
Kaunertal Expansion, 1,015 MW **Preparation stage** **Austria**	Several inter-basin transfers; multiple affected river reaches Impacts on river ecology, rafting, water availability for abstraction; significant opposition	Multiple release rules for most infrastructure components
Trevallyn, 96 MW **Operation stage** **Australia**	Bypass reach (~5 km) with reduced flow Biodiversity and recreation impacts	Minimum release from dam, modified over time

Project	Downstream Flow Issues	Management Measures
Teesta-V, 510 MW Operation stage India	Bypass reach (23 km) with reduced flow Peaking releases below powerhouse Multiple impacts including public safety	Minimum release from dam Warning systems
Kárahnjúkar, 690 MW Operation stage Iceland	Several inter-basin transfers; multiple affected river reaches Seasonal regulation; baseload generation Impacts on aesthetic value, sediment transport, fishing, etc	Releases based on hydrological conditions
Jostedal, 288 MW Operation stage Norway	Large inter-annual storage capacity, operated for flood control and hydropower Reduced flows downstream of several tributary intakes, reduced water level in a pond	Small-scale hydraulic works for mitigation
Santo Antonio, 3,568 MW Implementation stage Brazil	Low-head, run-of-river operation Potential erosion and quality impacts, closely monitored	Slow filling Spillway operation rules
Romanche-Gavet, 94 MW Implementation stage France	Run-of-river operation Bypass reach (~10 km) with reduced flows Impacts on fish and recreation	Minimum release from intake weir
Walchensee, 124 MW Operation stage Germany	Multiple diversions, including from upstream Isar River Peaking operation discharging into Kochelsee Aquatic fauna and flora, recreational fishing	Minimum releases with summer/winter variation on two high-priority reaches, introduced after ~70 years of operation
Kabeli-A, 38 MW Preparation stage Nepal	Bypass reach (15.6 km) with reduced flows Baseload operation during wet season, and peaking operation during dry season Impacts on aquatic ecology and religious activities in bypass reach; public safety downstream of tailrace	Minimum release from dam Ramp-up/down rules Sirens
Semla IV, 3.5 MW Preparation stage Sweden	Minor changes to flow arrangements between two lakes	Bypass flows through two channels maintained

Project	Downstream Flow Issues	Management Measures
Jirau, 3,750 MW Implementation stage Brazil	Low-head, run-of-river operation Discharge directly into Santo Antonio reservoir	Filling schedule over two wet seasons
Chaglla, 456 MW Implementation stage Peru	Bypass reach (15 km) with reduced flows Baseload generation and frequent spilling in wet season, daily peaking in dry season Main impact on fish habitat	Minimum release from dam (with micro-hydro) Ramping rules Aquatic offset
Keeyask, 695 MW Preparation stage Canada	Low-head operation Discharge directly into Stephens Lake reservoir Impacts on Lake Sturgeon spawning	Slow filling schedule 1 m reservoir operating range Continuous releases during spawning season Adaptive management
Reventazón, 306 MW Implementation stage Costa Rica	Bypass reach (4 km) with reduced flows Peaking operations Cumulative flow changes (lowest project in cascade) Impacts on rafting, fish, geomorphology, water quality	Minimum releases from dam and below tailrace Maximum spilling and flushing flows 3.5 km 'environmental channel' during filling Ramp rates Access to rafting companies Aquatic offset



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