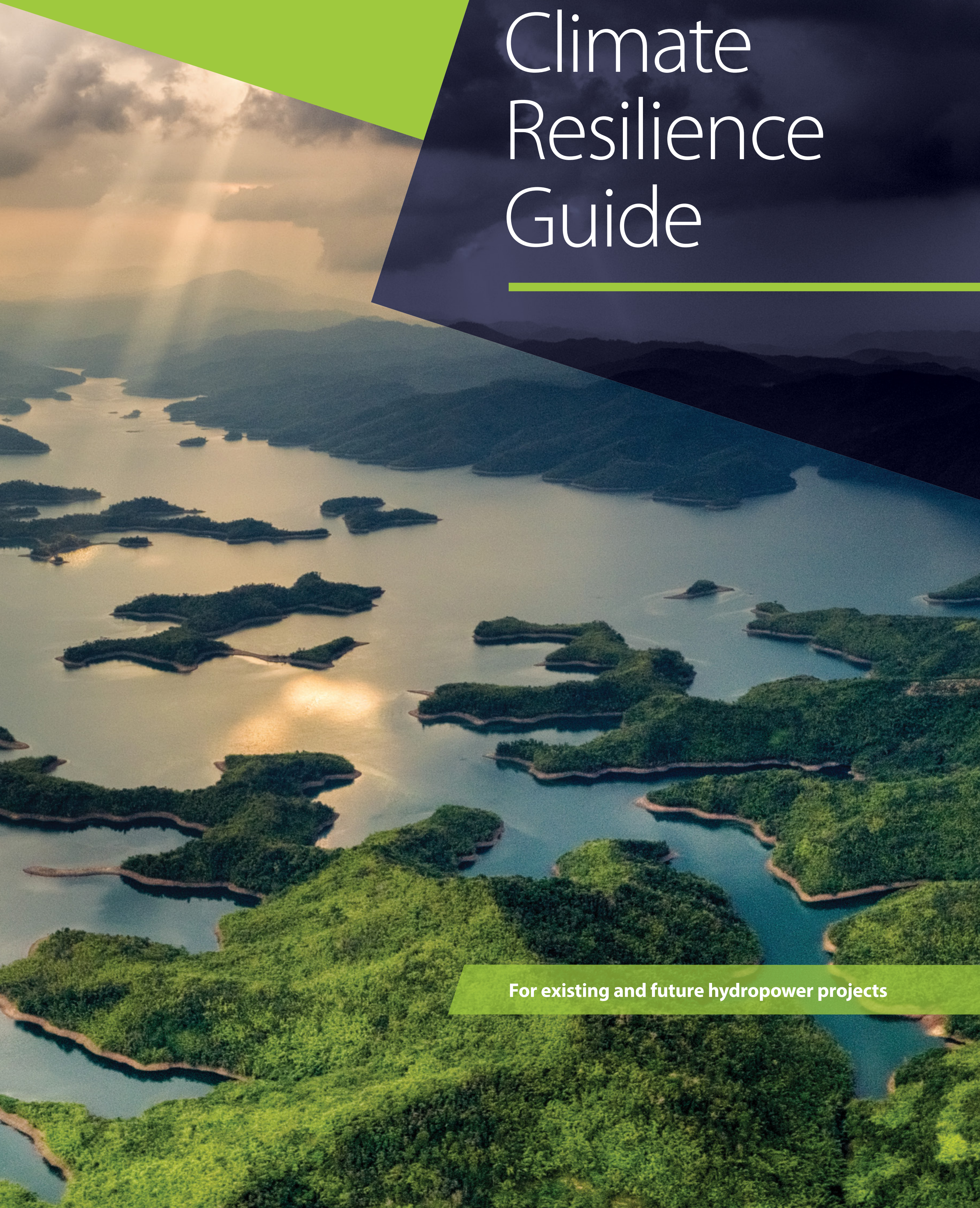

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Hydropower Sector

Climate Resilience Guide

For existing and future hydropower projects

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Acronyms and abbreviations

CMIP	Coupled Model Intercomparison Project
COP 21	UN Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP21) in Paris in December 2015
CRMP	Climate Risk Management Plan
DMU	Decision Making under Uncertainty
DMDU	Decision Making under Deep Uncertainty
EAP	Emergency Action Plan
EBRD	European Bank for Reconstruction and Development
EIRR	Economic Internal Rate of Return
ESIA	Environmental and Social Impact Assessment
ESG	Environmental, Social, Governance
EUFIWACC	European Financing Institutions Working Group on Adaptation to Climate Change
GCMs	General Circulation Models
GLOFs	Glacial Lake Outburst Floods
HESG	Hydropower Sustainability Environmental, Social and Governance Gap Analysis
HGIIP	Hydropower Good International Industry Practice
HSAP	Hydropower Sustainability Assessment Protocol
ICOLD	International Commission on Large Dams
IHA	International Hydropower Association
IPCC	Intergovernmental Panel on Climate Change
KGGTF	Korea Green Growth Trust Fund
MAX	Maximum
MER	Monitoring, Evaluation and Reporting
MIN	Minimum
ML	Most likely
NGOs	Non-Governmental Organisations
NPV	Net Present Value
O&M	Operation and Maintenance
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
PPA	Power Purchase Agreement
RCMs	Regional Climate Models
RCPs	Representative Concentration Pathways
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States Dollar
WBG	World Bank Group
WMO	World Meteorological Organization

Glossary

Concepts related to climate resilience and climate risks are common themes throughout the document. The glossary section intends to gather definitions for these concepts in the context of climate change and the hydropower sector.

Adaptation (functional)	Functional or non-structural instruments are modifications to operating policies. They can of course be applied alone without making any modification to the structural configuration and dimensions of the project, although in other cases an optimal balance of structural and non-structural adaptations may frequently be the most appropriate way of meeting the needs of climate change as defined in ICOLD Bulletin 169.
Adaptation (structural)	Physical modifications to existing projects or the construction of new infrastructure in order to alleviate the impacts of climate change. In some cases, these measures will be introduced to maintain the functionality, safety and effectiveness of the works and to satisfy the original design criteria in light of predicted climate change impacts. However, in other cases, it is likely that, as well as mitigating negative impacts arising from climate change, the structural changes may even result in improved performance as defined in ICOLD Bulletin 169.
Climate change	Climate change refers to a change in the state of the climate that can be identified (e.g. by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use as defined by IPCC.
Climate projection	A climate projection is the simulated response of the climate system to a scenario of future emissions or concentrations of greenhouse gases and aerosols, generally derived using climate models. Climate projections are distinguished from climate predictions by their dependence on the emission/concentration/radiative forcing scenario used, which is in turn based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised as defined by IPCC.
Climate resilience of a hydropower project	The capacity of a hydropower project or system to absorb the stresses imposed by climate change and in the process to evolve into greater robustness. Projects planned with resilience as a goal are designed, built and operated to better handle not only the range of potential climate change and climate-induced natural disasters, but also with contingencies that promote constructive, minimally-destructive failure and efficient, rapid adaptation to a less vulnerable future state.
Climate scenario	A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships, that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as an input for impact models. Although climate projections often serve as the raw material for constructing climate scenarios, climate scenarios usually require additional information such as the observed current climate. A climate change scenario is the difference between a climate scenario and the current climate.
Flood - design flood	Inflow of given return interval, to be discharged under normal conditions with a safety margin provided by the freeboard.

Flood - safety check flood	Inflow, which must be bypassed safely without causing dam failure. Some damage to the dam may be accepted.
Downscaling	Downscaling is a method that derives local- to regional-scale (10 to 100km) information from larger-scale models or data analyses.
Exposure	The situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas.
Glacial Lake Outburst Flood (GLOF)	Glacier thinning and retreat has resulted in the formation of new glacial lakes and the enlargement of existing ones due to the accumulation of meltwater behind loosely consolidated end moraine dams. The sudden lake discharge produces a torrent of water and associated debris known as GLOF.
Hazard	A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation. A hazard is characterised by physical parameters and a probability of occurrence.
Performance	Performance defines the capacity that the project can provide the strategic services or functions it is designed and operated for. It covers the full range of functions of a hydro asset: generation and economy, safety, environment, multi-purpose aspects (in some cases), etc.
Risk	Risk (or opportunity) is defined for a system or function as the combination of the Potential loss (gain) and the Likelihood of the climate event. Risk (opportunity) = Potential loss (gain) x Likelihood
Robustness	Performing reasonably well compared with the alternatives over a wide range of plausible futures.
Sensitivity test	A sensitivity test is an evaluation of the change in model output values that results from modest changes in model input values. The test is used to apportion model uncertainty to the uncertainty in model inputs.
Stress test	A stress test is a systematic evaluation of the system response to conditions greater than normal amounts of stress or pressure. The stress identifies the conditions (values of uncertain input variables) that result in unacceptable model performance (or breaking point) relative to a pre-defined performance threshold, which is the baseline. It also develops an understanding of the likelihood that the system will experience stresses beyond its breaking point within its lifetime.
Threat	A circumstance, action or event that might exploit a vulnerability with the potential to adversely impact an asset or a system.
Vulnerability	The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.
Weather generator	Weather generators are computer algorithms that produce long series of synthetic daily weather data. The parameters of the model are conditioned on existing meteorological records to ensure that the characteristics of historical weather emerge in the daily stochastic process. Weather generators are a common tool for extending meteorological records, supplementing weather data in a region of data scarcity, disaggregating seasonal hydro-climatic forecasts, and downscaling coarse, long-term climate projections to fine-resolution, daily weather for impact studies.

Contents

Foreword

As a low carbon technology, hydropower produces almost two-thirds of the world's renewable electricity generation and will make a significant contribution to achieving the targets of the Paris Climate Agreement and the Sustainable Development Goals.

While providing essential adaptation services to reduce the impacts exacerbated by climate change such as floods and drought, hydropower facilities can also be susceptible to climate risks due to their dependency on precipitation and vulnerability to natural disasters.

For hydropower operators, failure to adequately consider climate risks may lead to shortcomings in technical and financial performance, safety aspects, and environmental functions. If not designed and managed appropriately, hydropower projects could exacerbate the impacts of climate change on local communities and the environment. Furthermore, by not assessing climate change-related opportunities, investment decisions may not adequately recognise the role of hydropower infrastructure in providing climate-related services. This includes hydropower's role in supporting the greater use of less flexible forms of low-carbon electricity generation.

The Hydropower Sector Climate Resilience Guide has been coordinated by IHA and developed with technical and financial support from the European Bank for Reconstruction and Development (EBRD), the World Bank Group (WBG) and its Korea Green Growth Trust Fund (KGGTF). It is intended to help hydropower practitioners manage the risks of climate change. The guide responds to the need for clarity on good international industry practice for project owners, financial institutions, governments and private developers to consider climate risks in hydropower development and operations.

A beta version was developed by Mott MacDonald, under contract to WBG, and released in September 2017 after consultation with key stakeholders. The beta version was adapted and developed from the Decision Tree Framework, which incorporates concepts of decision making under climate-change uncertainty for the water sector, developed for the World Bank by Dr Casey Brown and Dr Patrick Ray. During 2018 and early 2019, organisations involved with new and existing hydropower projects around the world tested the guide to assess its applicability and practicality.

In January 2019, representatives from the testing process, as well as hydropower operators, lenders and the advisory expert panel, shared their experiences and feedback at a technical workshop. These important inputs have assisted in preparing this Hydropower Sector Climate Resilience Guide.

Hydropower resilience to climate change is essential to enable the development of new projects and to evaluate existing assets. Achieving consensus around this guide is extremely valuable not only for the hydropower sector but also for other infrastructure and technologies where there is a need to consider the impacts of climate change.

We would like to thank EBRD and WBG, which have provided invaluable support to IHA in its role as coordinator for the development of the Hydropower Sector Climate Resilience Guide. We must also thank the advisory expert panel for its hard work in refining the guide and all the organisations involved in this initiative.

In working together, we are helping to ensure the long-term sustainability of the hydropower sector and its role in clean energy systems and responsible freshwater management, while mitigating the risks presented by climate change.

Richard Taylor
Chief Executive
International Hydropower Association (IHA)

Introduction

Hydropower projects across the globe are being impacted by extreme weather events and changes in hydrological patterns in a world altered by climate change. Planning hydropower systems from a long-term, climate-resilient perspective supports climate adaptation for local communities and the environment and ensures that future generations inherit infrastructure that is not compromised by climate change.

To facilitate the development of hydropower infrastructure that can withstand the risks of variable climatic conditions, IHA, together with a range of partners, prepared this guide with the objective of providing practical and systematic guidance for hydropower engineers, operators and project owners to develop climate resilient projects.

Background

Climate change is defined by the Intergovernmental Panel on Climate Change (IPCC) as a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change is a fundamental threat to sustainable economic development and the fight against poverty.

At COP 21 in Paris in 2015, Parties to the UNFCCC reached a historical agreement to combat climate change and to mobilise significant financing for a sustainable future. The Paris Agreement set an unprecedented ambition to stabilise global temperature rise to between 1.5°C and 2°C. Assessing the consequences of climate change on key infrastructure assets and systems is a fundamental part of these considerations.

If the Paris goals are achieved, the consequences of climate change will be limited, though not eliminated. If the Paris goals are not achieved, these consequences will be much larger. In any case, the required transformation of energy, agriculture and other sectors of the economy may have significant implications for the economy of hydropower facilities.

Hydropower projects are directly influenced by meteorological, hydrological, geotechnical, glacial and geological processes, all of which are susceptible to climate change. Given the long design life of hydropower projects and their susceptibility to climate impacts, hydropower projects must be developed, operated and maintained to be resilient for a range of potential climate change scenarios.

Financial institutions and international organisations such as ICOLD have worked towards developing guidance for the wider community of water resources practitioners with up-to-date knowledge on climate science and climate impacts. However, until now there has been no widely accepted guidance on how to deal with climate change risks, specifically in the hydropower sector.

The Hydropower Sector Climate Resilience Guide was prepared by IHA in consultation with a wide range of professionals from the hydropower sector through a testing campaign using a worldwide pilot project during 2018 and with the support of an advisory expert panel.

Objective

The purpose of the Hydropower Sector Climate Resilience Guide is to provide a practical and useful approach for identifying, assessing and managing climate risks to enhance the climate change resilience of new and existing hydropower projects.

The guide responds to the need to provide international industry good practice on how to incorporate climate resilience into hydropower project planning, design and operations. The guide also seeks to evolve from the default use of historical data, the assumption that hydrological variability will remain the same over the lifetime of a project and the limited knowledge of how best to access, use and interpret climate change modelling and observed climate data. The conventional approach neglects to consider the short- and long-term impacts that climate change may have on investments due to the high uncertainty inherent to actual climate change predictions.

Intended audience

The guide's use is intended for hydropower practitioners that will follow the approach to assess climate change risks and identify climate resilience measures before reporting the outputs to the decision makers.

It is intended as a resource for project owners, financial institutions, governments and private developers, who will utilise the guide to make informed decisions on the development, rehabilitation and operation of hydropower projects. These stakeholder and decision maker groups comprise:

- Project owners, developers and operators – managers responsible for the planning, development, design, construction and operation of hydropower projects to consider climate risks in new and existing hydropower projects.
- Policymakers – officials from governments and national agencies looking at water and energy planning and regulatory aspects, who may use this guide as a framework to evaluate system risks.
- Financial institutions – project leads involved in the financing of new projects or the major rehabilitation and upgrade of existing hydropower projects, who request a climate risk assessment as a requirement for financing.

Core principles

The guide is designed to take users through a six-phase approach to incorporate climate resilience into hydropower project appraisal, design, construction and/or operation, to ensure that the project is resilient.

The applicability of the guide is underpinned by six core principles:

Applicability to any type and scale of hydropower project

Hydropower projects are characterised by the longevity of the infrastructure and are traditionally designed based on historical data. All hydropower projects, including storage, pumped storage and run-of-river, will need to cope with the risks of variable climatic conditions by having the capability to operate reliably and safely under an expected range of future climatic conditions and taking advantage of any opportunities that may occur.

Small- and large-scale hydropower projects are affected by climate change and at the same time provide climate change solutions for both energy and water systems.

Suitable for existing and future hydropower projects

The guide's application is relevant for both greenfield and existing projects. Hydropower adaptability and resilience to climate change will be key to enable the development of greenfield projects and the evaluation or rehabilitation of existing hydropower projects.

Adaptable to single and cascade projects

The guide provides an approach to assess climate change risks and evaluate resilience measures in a single-site hydropower project. The guide can also be referred to for cascade schemes as a single project. Hydropower cascade schemes are typically developed and operated in sequence to reduce the vulnerabilities and increase the benefits.

Relevant to any geography

The guide recognises the unique geographic and hydrological features in regions where the majority of hydropower development is currently being undertaken (South Asia, Latin America and Sub-Saharan Africa).

Climate change impacts vary significantly from a geographic perspective. The guide is designed to address all geographical and region-specific characteristics and challenges.

Aligned to the hydropower project's functions

The guide recognises the main functions of a hydropower scheme: reliable energy production, safety and environmental performance. Nevertheless, the climate risk and resilience analysis may encompass other services that hydropower projects offer such as load balancing, ancillary services, reservoir storage and socioeconomic functions based on the interests and concerns of the stakeholders.

Compatible with all data availability and quality

The guide recognises that the available hydrological and climate data can range in quality and quantity and is intended to be applied in all circumstances. The absence of high quality data should not refrain users from applying the guide.

The guide highlights the need for post-processing and refining of field data to discard outliers and ensure the quality of the data. The guide also provides guidance on global and publicly accessible data.

Complementing the Hydropower Sustainability Assessments Tools

The guide aims to complement the Climate Change Mitigation and Resilience topic of the Hydropower Sustainability Assessment Tools, comprising:

- The Hydropower Good International Industry Practice (HGIIP) Guidelines, a normative document that defines the expected sustainability performance and evidence required to demonstrate good practice in the sector.
- The Hydropower Sustainability Assessment Protocol (HSAP) and the Hydropower Sustainability Environmental, Social and Governance Gap Analysis (HESG) Tool, performance measurement tools which have built-in features to evaluate whether projects meet certain criteria for climate resilience.

Used individually or in combination, the tools promote international good practice and elevate the way projects are planned, developed and operated to advance sustainable hydropower. The HGIIP Guidelines are designed to support the assessment of project performance using the internationally-recognised HSAP and HESG Tool.

The Hydropower Sector Climate Resilience Guide may be useful to ensure that the evaluations by the HSAP or the HESG Tool adequately assess the resilience of a project. The guide may also ensure a robust process to evaluate project resilience required by rating systems to incentivise and improve the tracking of progress on adaptation and resilience.

Overview of methodology

The guide has adopted an approach to climate resilience for the hydropower sector, designed to address inherent climate change uncertainty. There are many causes of uncertainty ranging from the complexity of predicting multiple scenarios of future change with confidence to the lack of necessary data. Such an approach, often referred to as a 'bottom-up' approach, proves a valuable alternative to the top-down approaches used in climate risk assessments, the utility of which is often hindered by the lack of high confidence future climate projections derived from General Circulation Models (GCMs).

The guide consists of six phases, as shown in Figure 1 and Table 1, including preliminary requirements, a qualitative assessment of the project climate risks (Phase 1), an initial analysis (Phase 2), a climate stress test (Phase 3), a risk management plan (Phase 4), and lastly the monitoring, evaluation and reporting of the results (Phase 5). After the qualitative assessment in Phase 1, if projects are not deemed to have climate risk, the user can go directly to Phase 5.

The guide's approach employs stress tests for the identification of system risks (Phase 3), followed by simple, direct techniques for the iterative reduction of those risks through targeted actions that perform well over a wide range of future changes (Phase 4). At the end of Phase 4, if projects are not considered resilient for any of the options identified, the user should consider a new design to re-enter Phase 1 or abandonment.

Finally, a long list of the potential major climate impacts and stressors on hydropower, as well as indicators, is provided in Annex A, which also includes an overview of the different ways in which hydropower projects can be affected by climate change. Annex B provides examples of a risk and opportunity register and scoring methods. Examples of measures to improve the resilience of hydropower projects are provided in Annex C. For a further explanation on the approach adopted, Decision Making under Uncertainty (DMU), refer to Annex D. Refer to Annex E for an example of the climate stress test and resilience analysis.

Figure 1. The process of the Hydropower Sector Climate Resilience Guide.

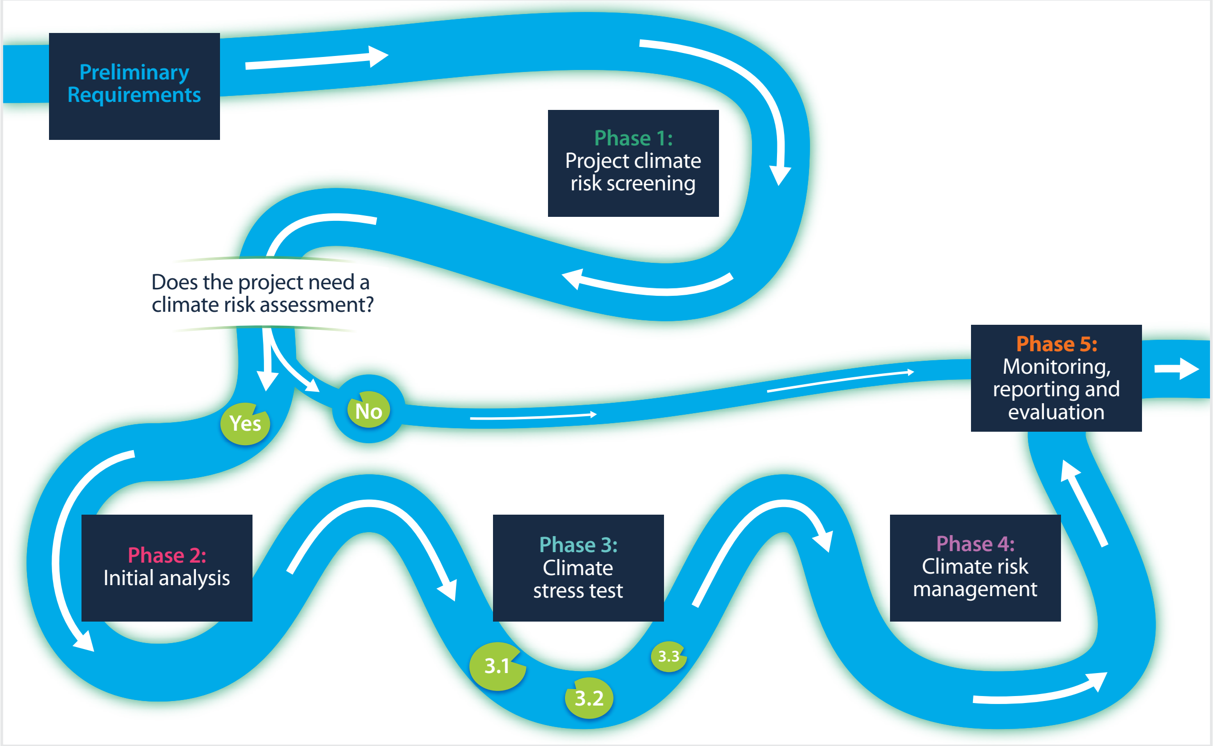


Table 1. Overview of the phases of the Hydropower Sector Climate Resilience Guide.

Preliminary requirements	**Phase 1:** Project climate risks screening	**Phase 2:** Initial analysis	**Phase 3:** Climate stress test	**Phase 4:** Climate risk management	**Phase 5:** Monitoring, evaluation and reporting
Objective: To meet requirements necessary to effectively use and apply the guide.	**Objective:** To understand the vulnerability of a hydropower project to climate change, considering its geographic, regulatory, technical and socioenvironmental characteristics.	**Objective:** Based on the analysis of climatic data and the definition of the baseline scenario determine the proper approach for Phase 3 (the climate stress test).	**Objective:** To assess project performance under different possible future climate scenarios in order to support decision making on resilient design and operation, and to quantify climate risks.	**Objective:** To adapt the project design – and/or make the project design adaptive – to ensure it is resilient to climate changes, while remaining cost-effective and economically sensible and sound.	**Objective:** To track how resilient the project is in operation and to allow the Climate Risk Management Plan to be monitored, reported on, evaluated and updated.
	Outcome: The development of a risk and opportunity register and performance criteria and metrics which will be the basis for the climate risk assessment.	**Outcome:** Hydro-climatic baseline scenario and refined risk and opportunity register.	**Outcome:** Updated risk and opportunity register.	**Outcome:** Project is designed to be resilient to climate change. Climate Risk Management Plan (CRMP).	**Outcome:** Monitoring, Evaluation and Reporting (MER) plan.
Requirement: 1. Understanding what climate resilience means for the hydropower sector 2. Management Support 3. Stakeholder engagement	**Step:** 1.1. Hydropower project characteristics and context 1.2. Hydro-meteorological data collection 1.3. Identifying uncertainties 1.4. Options for project adaptations 1.5. Risk and opportunity register creation 1.6. Performance criteria and metrics 1.7. Stakeholder engagement 1.8. Need for a climate risk assessment?	**Step:** 2.1. Data collection and analysis 2.2. Baseline definition 2.3. Determining approach for Phase 3 2.4. Stakeholder engagement 2.5. Risk and opportunity register update	**Step:** 3.1. Comprehensive approach 3.2. Semi-comprehensive approach 3.3. Limited approach 3.4. Stakeholder engagement 3.5. Risk and opportunity register update	**Step:** 4.1. Resilience measures identification 4.2. Options for project design 4.3. Resilience analysis 4.4. Risk and opportunity register update 4.5. Stakeholder engagement 4.6. Climate Risk Management Plan	**Step:** 5.1. Climate resilience monitoring plan 5.2. Evaluation and re-assessment of climate risks 5.3. Stakeholder engagement

Preliminary requirements

Objective: to meet requirements necessary to effectively use and apply the guide.

A number of simple requirements need to be met for the guide's effective application. These requirements, once met, will allow users to apply the guide in an effective way for the hydropower project they are planning, operating or rehabilitating.

Requirement 1. Understanding what climate resilience means for the hydropower sector

As a starting point, it is fundamental to understand the importance of climate change and the principle of climate resilience in the context of hydropower:

- What is climate change?
- What are the general implications of climate change on the occurrence of natural disasters and on the availability of water resources?
- What threats does climate change pose to hydropower projects?
- What is climate resilience (generally and in the hydropower sector)?
- Why is climate resilience specifically important for the main functions of hydropower projects (i.e. energy generation, safety, environmental performance)?
- What is climate modelling and how can global climate change scenarios be used in a hydropower climate resilience assessment?
- What approaches are there for building resilience?

Readers who are not fully familiar with these questions can refer to the Hydropower Sustainability Guidelines on Good International Industry Practice (2018), which includes a chapter dedicated to Climate Change Mitigation and Resilience.[1]

The 2016 ICOLD bulletin 'Global Climate Change, Dams, Reservoirs, and Related Water Resources'[2] also provides those practitioners in the large dams/reservoirs community with up-to-date knowledge on climate science and climate impact relevant to the hydropower sector.

Requirement 2. Management support

The preparation and implementation of a climate resilience strategy for a hydropower project requires resources and actions. Therefore, those involved in hydropower management should ensure that climate resilience is appropriately assessed and addressed, and should provide the necessary resources to undertake the preparation and implementation of a climate resilience strategy.

Managers should organise climate resilience, notably by assigning responsibilities to experienced or trained specialists. For major rehabilitations, modernisation or greenfield hydropower projects, the management should ensure that climate resilience teams/experts are fully coordinated with the engineering and ESIA team. The climate resilience assessment may be considered an integral part of the overall development of assessment of a project.

Climate change and hydropower practitioners should facilitate management support for their activities, for example through sharing the findings from early assessments when undertaking a climate risk assessment or securing senior-level support for the process through information on key business risks, in order to ensure that support is gained in terms of resourcing and budgets.

Requirement 3. Stakeholder engagement

Engaging with stakeholders from governmental institutions to local communities is fundamental to the successful application of the guide and the implementation of the results.

Governmental and institutional bodies have a key role to play in the consistency and efficiency of climate resilience strategies and actions across the various socioeconomic sectors and across the geographic regions within their jurisdiction. Establishing contact and engaging with governmental and institutional bodies may facilitate the collection of data and studies which form the basis to screen for the potential climate risks of the project in Phase 1.

In particular, policy makers, agencies and regulators that have statutory responsibility in the energy or water resources sectors have to deliver advice and a legal framework that takes into account the risks associated with climate change.

Supranational institutions from the energy or water sectors, transboundary river basin management organisations, national and local governments, investors, non-governmental organisations (NGOs), local or regional water resources agencies, meteorological and hydrological services and scientific institutes can also contribute to the resilience of a hydropower project by setting regulations, delivering institutional capacity building and training, creating dialogue platforms and producing and sharing knowledge that can foster the knowledge and experience of climate resilience for the hydropower industry.

Phase 1

Project climate risks screening

Objective: To understand the vulnerability of a hydropower project to climate change, considering its geographic, regulatory, technical and socioenvironmental characteristics.

Outcome: The development of a risk and opportunity register and performance criteria and metrics which will be the basis for the climate risk assessment.

This phase is a qualitative assessment of the climate change risks at the hydropower project level. The objective is to understand the vulnerability of a hydropower project to climate change, considering its geographic, regulatory, technical and socioenvironmental conditions based on a review of the project's characteristics and context, and initial data.

If the hydropower project shows vulnerability to climate change, the user should proceed with a climate risk assessment (Phase 2 to Phase 4). If the hydropower project is not vulnerable to climate change, then the user should proceed directly to Phase 5.

Step 1.1. Hydropower project characteristics and context

First, describe the project environment, its expected current and future role and function, recording relevant details pertinent to its context and basin that might be important in understanding the project's vulnerability to climate change:

- Country, region, river basin, site location and project boundaries.
- Development stage (planned, under construction, operating, under major rehabilitation).
- Describe the project (e.g. type, scale, primary uses, operating curve and regime (base load or peaking), ancillary services, integration in a cascade system and planned modifications, if any).
- Indicate whether the project is designed to satisfy other purposes (i.e. flood control, irrigation, public water supply) throughout its project life.
- Owners, financiers, operators, regulators and key stakeholders.
- Describe the broader basin characteristics and define the geographical boundary of the project basin. Identify any major existing or future issues with water resources and constraints within the basin.
- Geography, geology, hydrology, land use and land cover, and upstream and downstream water/river uses.
- Health, safety, environment and social aspects.
- Unique regional aspects (e.g. glacier-fed projects, extreme wet and dry seasons, known effects of macro-climatic phenomena such as El Niño or La Niña).

- Presence of aquatic or terrestrial species or areas of conservation interest (legally protected or internationally recognised) in the project's area of influence.
- Key existing or planned regulations and policies from the energy (i.e. pricing, market), water or environment (i.e. license, minimum flow, basin management rules) sectors to be considered in a climate change context.
- Future planned operation mode and possible alternative methods.
- Identify all other possible (existing, planned or opportunistic) upstream and downstream water issues which are likely to influence the project throughout its life, including possible medium- to long-term developments (flood control, irrigation, public water supply, tourism, ecosystems).
- Describe the electricity grid served by the project, including whether it is an isolated or interconnected grid and the relative importance of the project for electricity supply service continuity in the grid.

Step 1.2. Hydro-meteorological data collection

In order to support the decision-making process at the end of Phase 1, it is necessary to establish a time horizon and collect and review existing hydro-meteorological data or studies to reach an informed decision. If the assessment continues to Phase 2, this data will form the basis for the data analysis of Step 2.1.

- Establish the time horizon for the climate risk assessment agreed upon with relevant stakeholders. This time horizon will be project-specific, however, a minimum time horizon of 30 years as recommended by the World Meteorological Organization[3] is a reasonable basis for all greenfield developments and for major rehabilitation projects.
- Collect and review the general available historical meteorological, hydrological and climatic data and define assessment boundaries by identifying the key sources of data at the regional, country and site levels. For example:
  - Climate change relevant for the region from the latest reports published by the IPCC.
  - Relevant climate studies and documentation from the recent past for the region, country, river basin or at site level.
  - National and/or regional assessments on climate vulnerability, related regional energy plans and policies.
  - Detailed field data (at the country, region, river basin and site level) on:
    - Climatology – What climate stations are available in the catchment and adjacent catchments (focus on precipitation and temperature)? What is the duration of records?
    - Hydrology – What stream gauging stations are available in the catchment and adjacent catchments? What is the duration of records?
    - Sedimentation – Has any sediment monitoring been undertaken previously?
    - Catchment land cover and land use – Are satellite images available to assess the catchment land use/cover trends?
    - Glaciology/permafrost (where applicable) – Records, trends and historical events related to glaciers and glacial hazards or permafrost in the catchment and adjacent catchments.
    - Natural hazards – Is the site downstream, exposed to or close to any natural hazards (geological hazards, earthquakes, avalanches, debris flows, etc)? Is there a history of natural hazards in the region?
- Gather data on observed extreme events and natural disasters which have occurred across the river basin or catchment. Identify any indirect basin sensitivity such as land use changes or trends. Use data from the operations, nearby meteorological stations, water resource management plans or other published reports, local stakeholder knowledge, and newspaper/website reports on thresholds reached or exceeded from previous events[4].
- List any outstanding gaps and define any new data collection or system to be set up. Present and discuss the findings to relevant stakeholders identified in requirement 3.

In cases of limited data, it is possible to use publicly available data from reliable sources such as the World Bank Climate Change Knowledge Portal[5], satellite data or re-analysis of meteorological data. Further information on data analysis is given in Step 2.1.

Step 1.3. Identifying uncertainties

Climate change can be a threat multiplier that may accentuate some of the risks that affect project performance (e.g. debris flows or geo-hazards identified in Step 1.2). Likewise, there may be opportunities that may be enhanced by climate change (e.g. increased energy demand).

In addition to the data collected in the previous step, other parameters that are not specifically viewed as related to climate change but might affect the screening analysis if ignored completely should be considered. Any trend or historical changes in these parameters as well as expected/potential future changes might be important to define the project's risks and opportunities. Examples of these parameters are in Table 2.

Step 1.4. Options for project adaptation

To inform the project screening analysis, it is necessary to conceptualise the different potential risks and opportunities (using Annex A) and think of the different options for increasing resilience and flexibility of the project through both structural and functional adaptation measures (using Annex C). Some examples could include (but are not limited to):

- Operating flexibility.
- Options for power generation design change (for example variable output/generation that may mean a different installed capacity is selected).
- Options for safety design change (e.g. increased spillway capacity).
- Water storage management flexibility (e.g. through adapting the operating regime of the project).
- Options for natural hazard mitigation (e.g. increased landslide protection).
- Possibility to modify downstream water releases.

Table 2. Examples of the parameters for which climate change can be a threat multiplier.

Economic	Environmental & social	Regulatory	Technical
• Cost of debt • Cost of equity • Electricity pricing • Commodity pricing (e.g. steel price) • Energy and capacity demand forecast • Interest rate • Discount rate • Availability and willingness of investors to work in the region	• Requirements for environmental flow • Development limitations identified in ESIA • Regulatory changes • Displaced and resettled communities • Public policy – political support for project • Issues related to intergenerational equity	• Country and regional constraints on the operation of the project • Details of the Power Purchase Agreement (PPA) agreed between the developer and the power purchaser • Regulatory constraints on power trading imposed by power pools	• Wind speed for transmission lines maintenance • Switchyard maintenance

Step 1.5. Risk and opportunity register creation

Based on steps 1.1. to 1.4., prepare a register of the potential risks and opportunities related to climate change. The risk and opportunity register must cover all potential climate stressors relevant to the project. See Annex A for a list of potential climate stressors that may be relevant.

The register should be as exhaustive as possible and include the threats/opportunities associated with each climate stressor and an estimate of the likelihood and potential loss/gain of each threat/opportunity. The estimation of likelihood and potential loss/gain will determine the risk level. An example risk and opportunity register is provided in Annex B.

In the following phases, additional information will refine the risk and opportunity register and quantify the risks.

Step 1.6. Performance criteria and metrics

Identify the project performance characteristics that could potentially be affected by climate change and define the criteria with regards to climate change. The performance criteria are likely to be related to main functions like generation, safety and environment.

- Generation functions, for example:
  - Adequacy of power equipment design with regards to inflows and market variabilities (number of turbines and installed capacity, operating range variable speed, etc).
  - Exposure of intake structure to variations in inflow conditions (water level, velocity fields, etc).
  - Performance and durability of conveyance infrastructure and penstocks.
  - Associated station infrastructure exposure to climate change (service and transmission lines, switchyard, etc).
  - Sediment management.
- Safety functions, for example:
  - Spillway capacity to discharge extreme floods based on recent flood assessments.
  - Dam crest/freeboard and reservoir operation.
  - Reliability of access roads.
  - Natural hazards (geological processes, avalanches, debris flows, etc.).
  - Sediment impact on bottom outlet blockage, upstream flooding risk, etc.
- Environmental and multi-purpose functions (can be included as relevant in the generation or safety functions), for example:
  - Potential increase of minimum flow requirements for species or ecosystems of conservation interest.
  - Sediment yield management.
  - Upstream and downstream fish migration.
  - Reservoir management: water level, water quality.
  - Downstream water demand for social and economic activities (conflict prevention, anticipation of demand increase, etc).
  - Safety issues related to rapid flow variations.

Define appropriate metrics to measure successful performance of these criteria. These performance metrics must cover all the potential risks and opportunities recorded in the register, and must be based on the following points:

- An inventory of the strategic objectives (functions, services, etc) that are core to the efficiency and safety of the hydropower project from the perspective of maximising energy generation and maintaining overall safety of the asset and the environmental performance.
- They should address all strategic objectives, although they are not specific to climate and should reflect how strategic performance can be affected by climate change stressors.

- They must be consistent and robust over time, as long as the strategic objectives remain valid.
- They must be translated into indicators consistently defined (qualitatively robust over time, knowing that numbers may change over time or from one situation to another one).

The performance metrics will be used throughout phases 2 to 5.

Step 1.7. Stakeholder engagement

The results from steps 1.1. to 1.6. must be shared and discussed with the relevant stakeholders. Under Phase 1, the relevant stakeholders notably include the team in charge of the project's design (future projects) or operation (existing projects), as well as all third parties who are directly or indirectly interested in the performance metrics. In particular, these third parties include parties that would be impacted by a poor environment or multi-purpose performance. The engagement process should provide stakeholders with the opportunity to comment on the performance criteria to ensure that their goals are represented in the metrics. Relevant documentation should be shared to ensure the process is open and transparent.

Step 1.8. Need for a climate risk assessment?

Qualitatively assess whether climate change may have a significant influence on the project, focusing on project performance metrics that may not be achieved or risk thresholds that could potentially be exceeded. Table 3 shows the questions which need to be answered to assess whether a climate risk assessment is necessary.

If the answer to at least one question is yes, it is necessary to undertake a climate risk assessment: proceed to Phase 2. If the answer to all questions is no, proceed directly to Phase 5.

Table 3. Questions to assess the need for a climate risk assessment.

Could a change of the hydrological regime significantly affect the hydropower project's economic viability?	Yes/No
Could a change in the hydrological regime affect service continuity/access to electricity in the region it serves?	Yes/No
Could any of the performance metrics defined in Step 1.6. be unachievable by potential climate change effects?	Yes/No
Would a breach of the project's main dam or other associated infrastructure have significant adverse consequences on downstream populations, strategic infrastructure or protected ecosystems?	Yes/No

Phase 2

Initial analysis

Objective: Based on the analysis of climatic data and the definition of the baseline scenario, determine the proper approach for Phase 3. Climate stress test.

Outcome: Hydro-climatic baseline scenario and refined risk and opportunity register.

In this phase, an assessment of the climatological boundary conditions and the relevant project characteristics will inform whether the climate during the lifetime (or remaining lifetime) of the project is likely to be substantially different from the climate on which the project design was (or is being) based.

The data analysis will help to define the hydro-climatic baseline scenario (Step 2.2.) as a reference point to apply the stress test. In Step 2.3., based on the data analysis of Step 2.1. and the project risks identified in Step 1.5., determine the proper approach to apply the climate stress test in Phase 3.

Considering the findings of the assessment in this phase, the preliminary risk and opportunity register developed in Phase 1 is further refined.

Step 2.1. Data collection and analysis

Evaluate the data quality and quantity collected in Step 1.2., and gather more data if necessary. In Phase 2, the dataset is needed to perform a statistical analysis, detect trends and develop rudimentary confidence bounds on ranges of plausible future climate.

Dataset collection

If the data from Step 1.2. is not sufficient to do an initial analysis, additional data should be gathered. This includes data on any available climate variables deemed relevant (e.g. sub-daily temperature and precipitation, solar radiation, humidity, wind).

Using a spreadsheet or statistical software package, compile all relevant historical hydro-climatological data, including both the observations of local meteorological stations within (or adjacent to) the river basin and all available global gridded climate datasets with temporal coverage in the required range.

Generally, the most reliable data is local ground-level observations. However, quality assessment is important; local data products should be compared with global data products (e.g. climate data from the US National Centre for Atmospheric Research[6]) to establish a single consistent baseline. Global gridded datasets can be used to fill gaps in the local observations and also to smooth local observations across large spatial domains and extend records of insufficient length, especially when the basin under evaluation includes large or drastic elevation gradients.

Data analysis

In order to inform the choice of baseline, analyse the quality of the data and use established methods to fill gaps in historical records, evaluate statistics (e.g. mean, standard deviation, coefficient of variation), persistence (e.g. autocorrelation and seasonality) and trends (e.g. using the Mann Kendall test) for all data sources for the full duration of the meteorological record.

If the statistics of the various meteorological datasets are in poor agreement, the locally observed record can be used to bias-correct the global gridded datasets to develop continuous (in space and time) records of historical climate.

The estimation of the long-term mean values of precipitation and flow might be subject to considerable uncertainty, especially in areas with strong interannual variability, trends or low frequency oscillations of climate. If possible, this uncertainty in the long-term mean values should be quantified. This can be done using analyses of historical series, supported by statistical methods or other approaches (such as wavelet decomposition).

For hydrologic, hydraulic and most other modelling efforts, overlap in temporal coverage is needed in all available datasets. The first step is to determine the time period available for model calibration. This will be the period during which all data is available and continuous (precipitation, temperature, streamflow, land use, etc). Typically, the period of streamflow record will be the limiting factor for modelling efforts.

Within the timeframe of the historical streamflow record, develop a continuous record of climate by either using local observations directly (if sufficient) or using the local observations to bias-correct the global gridded climate datasets.

Historical data, whether local ground observations or global gridded datasets, describes local historical behaviour of precipitation, temperature and other relevant hydro-climatic variables, and also indicates trajectories to inform expectations for the future. On the other hand, climate change projections (from experiments performed with General Circulation Models (GCMs) and Regional Climate Models (RCMs)) provide insight into behavioural changes that the climate might undergo in a future of ocean-atmospheric processes altered by warmer ambient temperatures. The climate change projections are most meaningfully consulted for questions of change relative to historical (e.g. more or less total annual precipitation, slightly warmer or much warmer winters, more or less net solar radiation) as opposed to questions requiring basic statistics of local future climate (e.g. future local precipitation mean/variance, future local max daily temperature). GCMs tend to be highly biased towards local climate statistics, but can provide credible, useful information regarding their directionality of change.

Climate change projection review

Identify worst cases to consider in Step 2.2. based on observed climate trends, plausible climate change scenarios and insights gathered by reviewing the latest IPCC ensemble of projections from the Coupled Model Intercomparison Project (e.g. CMIP5). For instance, scenarios can be grouped together (e.g. warmer and wetter) to allow for ease of comparison, communication and the development of an internally consistent future to be applied through the assessment.

Review climate change projections of relevant variables, such as the annual averages, seasonal variability, or changes in monthly maximum and minimum values of precipitation and temperature. As a minimum, look at two different Representative Concentration Pathways (RCPs) (e.g. 4.5 and 8.5) and a minimum of two future 30-year time periods (most relevant to the project and asset lifetime).

It is important to consider at least the full range of the current ensemble of climate projections, but care must be taken not to draw unjustifiable confidence around the full bounds of the uncertainty space. The GCM ensemble (whichever generation it happens to be) does not delimit the full universe of possible future climate change. For example, consider using the 10th, 50th and 90th percentile change values (e.g. a reduction in precipitation) from the full range of the latest models (i.e. all CMIP5 models used in the latest IPCC Fifth Assessment Report) to achieve a defensible range of plausible future change.

For regionally-specific climate change projections, a number of sources are available, including the WBG's Climate Change Knowledge Portal[7].

Users may also find it useful to access the ClimGen Country scatter plots[8] produced by the University of East Anglia[9] using the latest IPCC data (from the data distribution centre[10]).

Step 2.2. Baseline definition

The definition of the baseline is a foundational part of a climate risk assessment and is the point of reference for the climate stress test conducted in Phase 3. For the assessment of existing hydropower projects, the baseline would typically be the climate conditions on which the design was based or which were prevailing during the period of recent operation. For the assessment of greenfield hydropower projects, the baseline represents the climate conditions for which the initial design is made.

Especially for greenfield projects, the baseline definition relies on the results of trend analysis described in Step 2.1. because the historical period may no longer be representative of the current climate state.

The trend analysis in Step 2.1. provides an informed comparison of the trends observed in the historical record with the projected future climate derived from the GCMs. If the trends and the projections agree on the approximate magnitude of expected changes, this may inform the baseline and the confidence and type of likelihood function used in Phase 3.

With the insight from the historical observations and climate change projections, establish a consistent baseline against which to measure potential changes to future system performance.

- In many cases, the baseline would be the hydro-meteorological conditions of the most current 30-year period.

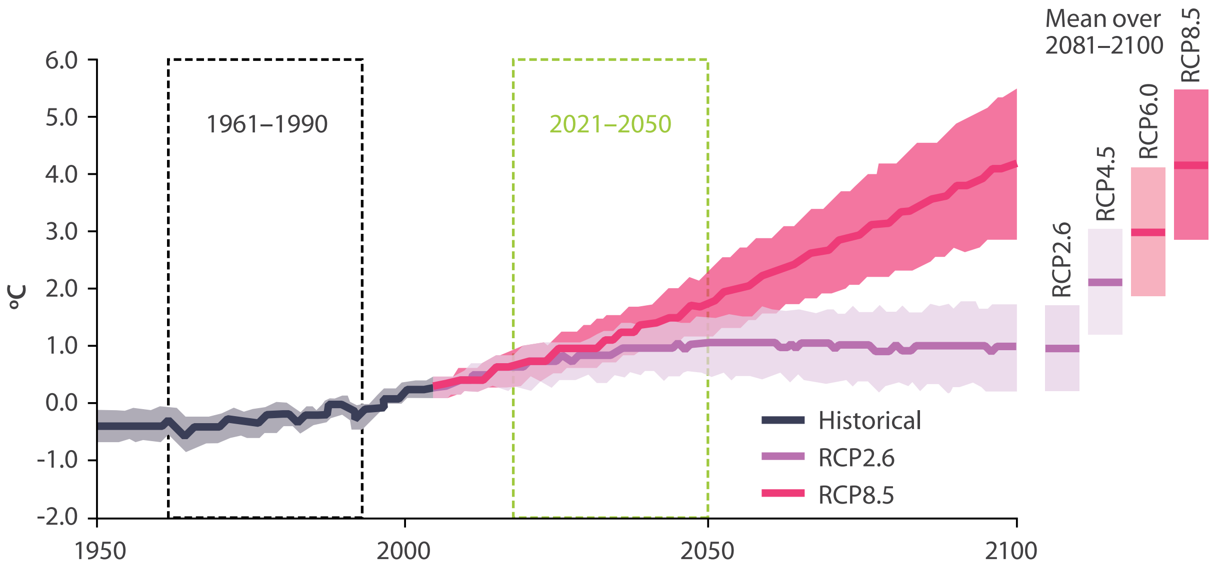
- The last 30 years of data is not always available, as is the case in many regions where the hydro-meteorological networks have deteriorated in the latter stages of the 20th century; however, there is data availability from more than 50 years ago. It has therefore been common practice to base the design of hydropower projects in these regions on data for the period 1961-1990, since for this period data of reasonable quality is typically available. As illustrated in Figure 2, this bares a significant risk that the design is inappropriate for the climate and inflow conditions expected for the first 20-30 years of operation, which is typically the period considered in evaluation of economic project performance (e.g. 2021-2050). This risk is even higher if the mid- and long-term future is considered, which might be the physical lifetime of the project.

So, in both cases, if there is high confidence in a past trend, it may be reasonable to establish, as a baseline, a 30-year climate trace which is identical to the historical pattern, except with an adjustment to the trending climate variable to better represent current or near-future conditions (e.g. a 30-year climate trace with increased mean daily temperature within the range that might be extrapolated throughout the anticipated lifetime of the project using the current or projected temperature trend).

Step 2.3. Determining approach for Phase 3

The approach required for the Phase 3 climate stress test can be determined using the criteria outlined in Figure 3. The criteria are based on the level of project risks recorded in the risk and opportunity register created in Step 1.5. and the dataset limitations, in terms of quality and quantity, analysed in Step 2.1.

Figure 2. Projected changes in global annual mean surface temperature relative to 1986-2005 (IPCC).



Nevertheless, considerable climate change risks to project performance, as concluded in Step 1.8., warrant a careful, thorough approach to the assessment of climate change. It is also recommended that all projects should be evaluated using the fully comprehensive approach.

Alternative approaches to this evaluation can be described as follows (illustrated also in Figure 3):

- For projects with medium to high potential risks as recorded in the risk and opportunity register:
  - If low resolution in hydro-meteorological data which does not allow the creation of a continuous hydrological model in at least daily time steps and/or larger ensembles of RCM projections are not available, then a semi-comprehensive approach with a monthly-step hydrological model and/or a limited number of scenarios should be performed.
- For projects with low potential risks, as recorded in the risk and opportunity register:
  - If good quality datasets are available, it is recommended that at least a semi-comprehensive climate stress test be undertaken.
  - If the datasets are insufficient and no other means for augmenting the data are available or cost-effective, then a limited approach might be taken.

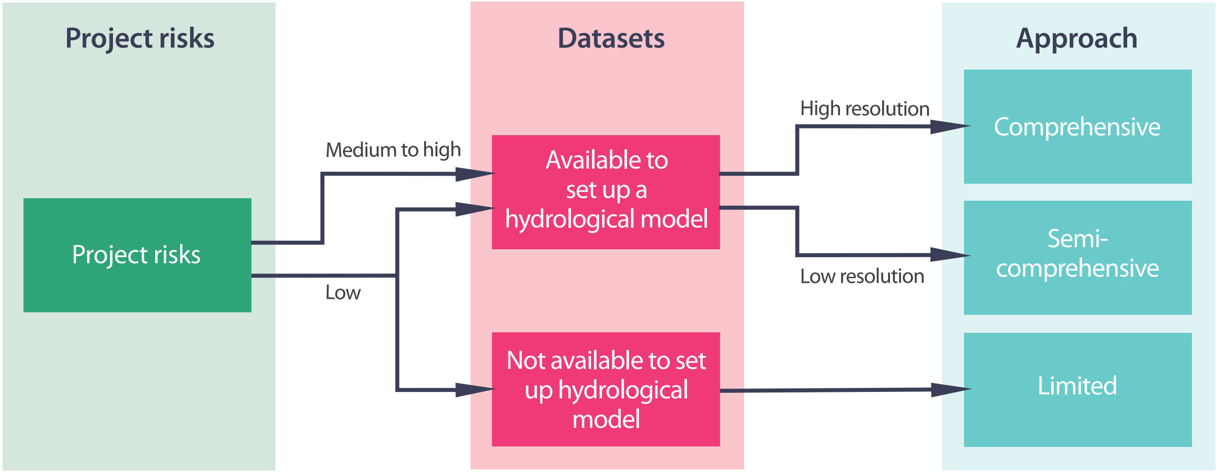
In case of projects with high risks but with limited data in terms of quality and availability, data collection should be set up in order to guarantee at least a semi-comprehensive climate stress test.

Step 2.4. Stakeholder engagement

The results from Phase 2 should be shared and discussed with the relevant stakeholders. In Phase 2, the relevant stakeholders include entities involved in climate change forecasting, planning and management such as governmental bodies, funding agencies, technical services or institutions. Downstream stakeholders involved in activities related to the use of the river or its water should also be consulted if they have not been fully engaged during the Phase 1 consultation or if new aspects need to be discussed with them.

The decision on the baseline and the required stress testing approach must be discussed with these stakeholders as it will be decisive for the outcome of the climate risk assessment.

Figure 3. Alternative approaches to carry out the Phase 3 climate stress test, subject to level of project risks and datasets availability and quality.



Furthermore, the initial risk and opportunity register developed in Phase 1 should be discussed with the stakeholders and additional risks and opportunities that might arise from the findings in steps 2.2. and 2.3. should be identified and included in an update of the register in Step 2.5.

The engagement process should provide stakeholders with the opportunity to comment on the rationale for the approach selected for Phase 3. Relevant documentation should be shared to ensure the process is open and transparent.

Step 2.5. Risk and opportunity register update

As a final step in Phase 2, the initial climate risk and opportunity register developed in Phase 1 should be updated. The update should consider the improved understanding of the historical and future climate conditions developed in steps 2.1. and 2.2. as well as new risks and opportunities identified during the stakeholder consultation in Step 2.4.

Phase 3

Climate stress test

Objective: To assess project performance under different possible future climate scenarios in order to support decision making on resilient design and operation, and to quantify climate risks.

Outcome: Updated risk and opportunity register.

Phase 3 assesses the performance of the project considering the additional stress that may be imposed by climate change through a climate stress test, according to the approach determined in Step 2.3.

Table 4 shows the modelling methods and the choice of the possible future climate scenarios suggested to perform the corresponding climate stress test for each of these approaches.

The performance of the project, either existing or planned, is assessed with respect to the risks already identified and updated in the risk and opportunity register in Step 2.5. in relation to the main functions defined in Step 1.6. The baseline scenario is taken as the reference as defined in Step 2.2.

Table 4 also provides some guidance regarding modelling of extreme flood events, which is relevant to hydropower projects; however, it is subject to considerable uncertainty. The estimation of the magnitude of extreme events under conditions of climate change is associated with even higher uncertainty. Therefore, in many cases without sufficient data, it will not be possible to quantify the impact of climate change and the assessment of risks related to extreme flood events will have to be done in a qualitative way.

At the end of this phase, the outcome is how the project would perform under different possible climate futures and the identification of the conditions under which the project's performance fails. Phase 3 provides an understanding of whether the conditions to which the project is vulnerable are of sufficient concern (in terms of likelihood and impact) to warrant protective adaptation measures. Phase 4 will determine these adaptation measures. If no risks are revealed when applying the climate stress test, the project has been designated resilient to climate change and thus the assessment continues to Phase 5.

Table 4. Approach to climate stress test.

Approach	Method - hydrological model	Method - modelling extreme flood events	Future climate scenarios choice	Stress test
Comprehensive	Hydrological model with daily time steps; direct approach	• Flood frequency analyses supported by numerical modelling • PMF simulation based on statistical or meteorological PMP approach	Ensemble of GCM or RCM-based climate projections	Multi-variate sensitivity analyses of (at least) precipitation and temperature in mean and extremes
Semi-comprehensive	Hydrological model with at least monthly time steps; delta change or direct approach	• Flood frequency analyses • PMF simulation, as in comprehensive approach, or Clausius-Clapeyron equation approximation	Observed trends and at least three locally-credible GCM or RCM-based climate projections (optimistic, central, pessimistic); as discussed in Step 2.2., the 10th, 50th, and 90th percentile change values are recommended	Uni- or bivariate sensitivity analyses of precipitation and temperature; for PMF with PMP variations
Limited	• Regression Models • Budyko-type Models • Historical climate analogies model	• Empirical methods • Flood frequency analyses	Observed trends and centroid of the current GCM ensemble	Uni- or bivariate sensitivity analyses of precipitation and temperature

Step 3.1. Comprehensive approach

This approach is a multi-variate sensitivity analysis which assesses the impacts of the changes in climatic variables (such as precipitation and temperature) on climate variability (interannual, seasonal, short-term) and extremes. Refer to Annex E for an example of this approach.

Hydrological modelling

The hydrological model in this approach must be a continuous model with daily or higher data resolution. Climatological data for the model can be also created by using a weather generator[11].

Either conceptual models or physically-based models can be applied. Physically-based models require a proper parameterisation to represent the runoff generation process. These models are relevant in catchments where meteorological variables other than precipitation and temperature (e.g. radiation and wind speed can have a strong influence on snowmelt and evapotranspiration) play an important role in the runoff generation process or where land use changes have to be considered.

The models have to be carefully calibrated (parameterised) and should be validated using separate historical periods (split sample test). The model performance for the calibration and validation periods should be assessed both qualitatively (based on comparison of observed and simulated flow hydrographs) and using quantitative measures (e.g. Kling-Gupta Efficiency, Nash-Sutcliffe Efficiency, bias, sum of squared residuals, and/or other statistical measures). Major model biases cannot be accepted. It is important to ensure that a good fit of the hydrological model is achieved for both the calibration and the validation periods.

Once the calibration and validation processes are completed, the hydrological model (coupled with the hydropower and the economic models) can be used for stress testing. The hydrological model may also have to be extended by a water management model, allowing for consideration of different development scenarios in the basin upstream. This can be important for basins which are under water stress and where climate change acts as a potential threat multiplier (as identified in Step 1.3.).

Extreme flood events

In the context of climate change, it is important to develop a good understanding of changes in extreme events to calculate the design floods for a hydropower project. Design floods and safety check floods are usually derived from flood frequency analyses and/or from Probable Maximum Flood (PMF) assessments.

- Flood Frequency Analyses

  Flood frequency analyses are statistical methods which allow assessment of the magnitude of floods of a given return interval based on analyses of observed (or simulated) samples of flood events. In order to assess the impact of climate change on flood frequencies, a flow series of at least 30 years needs to be simulated by a continuous hydrological model.

  Hydrological models provide an understanding of the underlying processes for generation of extreme flood events in the catchment of the projects. In the simplest case, the model is run with historical meteorological input, which is then altered in order to assess the impact of possible climate changes on flood hydrology.

  Stochastic weather generators (calibrated based on historical records) can significantly enhance the process because they allow to simulate very long time series, thereby reducing the uncertainty in flood frequency analyses arising from the limited sample size of the historical records.

  The simulations will determine the delta in the flood magnitudes (of a given return interval) simulated for historical and future conditions. This gives an indication of whether the future conditions can expect an increase or decrease in the flood magnitudes in comparison to the baseline condition.

  In case of an increase in flood magnitudes, the delta found for given return intervals should be superimposed on the flood magnitudes derived from historical records to adjust the design flood for the future conditions.

  In case of a decrease, it is not recommended to adjust or reduce the design floods derived from flood frequency analyses.

- Probable Maximum Flood (PMF)

  PMF estimates are based on a deterministic concept where the Probable Maximum Precipitation (PMP) is determined and then transformed into the PMF by a precipitation-runoff model.

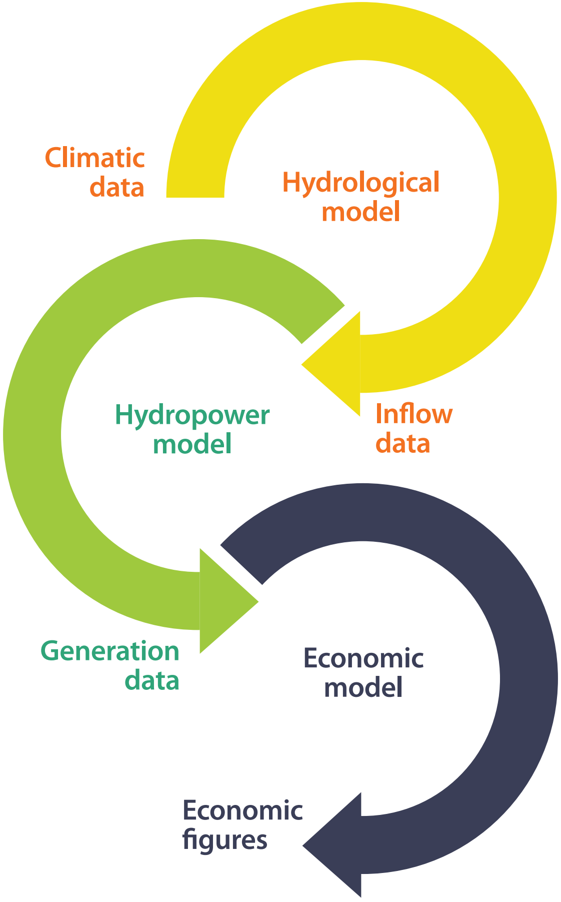
  In a comprehensive approach, to account for future climate conditions, the PMP calculation requires a meteorological approach (e.g. as described by WMO, 2009) which allows for varied meteorological parameters that might be affected by climate change.

  The most sensitive parameter in PMP assessments, with respect to climate change, is probably the maximum dew point temperature as it defines the moisture availability (precipitable water). If, for the future conditions, higher air temperatures are assumed compared to the baseline conditions, this also has to be reflected in the dew point temperatures considered in the PMP assessment. Other parameters that might be affected by climate change include depth-area curves, storm types and storm efficiencies. For each of the PMP scenarios a PMF hydrograph can be simulated using a properly calibrated hydrological model (continuous or event-based type).

  This procedure should be repeated for a range of possible climate futures. Since a meteorological PMP assessment is a time-consuming task, the number of scenarios to be assessed in a climate stress test would typically be quite limited. The focus should therefore be on a few relevant scenarios (e.g. the most likely scenario as well as the worst-case scenario) covering the maximum temperature increase that is expected under a warmer climate future.

Climate change might intensify hydrological and geological hazards including GLOFs, landslides and ice fall that can impact the hydropower project. For major hazards identified, the development of hydrodynamic or rheological numerical models and geological and glaciological site investigations will inform the assessment of extreme events.

Figure 4. Representation of models that can be used in the stress test.



Future scenarios and climate stress test

In order to assess the generation and economic performance of a hydropower project under conditions of climate change, the hydrological model needs to be coupled with hydropower and economic models. Figure 4 represents a flow of coupling models to simulate inflow data, generation data and economic figures.

The inflow data that results from the hydrological model provides the input for the hydropower model. The hydropower model, which typically includes models that capture reservoir and plant operation, transforms the inflow data into generation data. Finally, the economic model transforms the generation data into economic figures. These economic models might be methods of discounted cash flow based on a given tariff scheme or energy price projection.

Initially, the stress test should simulate the hydropower generation (using a hydropower model) and economic performance (using an economic model) for the baseline.

Then, the stress test assesses the range of possible climate scenarios identified in Step 2.2. as well as perturbed stochastic climate traces that capture the range of possible climate futures represented by the full current ensemble of GCM or RCM-based climate change projections, as well as a wider range of possible climate futures, in order to explore the boundaries of system failure.

Step 3.2. Semi-comprehensive approach

This approach is a uni- or bivariate sensitivity analysis of precipitation and temperature.

Hydrological modelling

The hydrological model in this approach must be a continuous water balance model with at least monthly resolution, but daily resolution is preferable. As is the case in Step 3.1., either conceptual models or physically-based models can be applied.

Unlike the comprehensive approach (Step 3.1.), some bias in the hydrological model might be accepted. This bias, however, needs to be corrected before performing the stress test. Depending on the bias of the model two different modelling approaches can be considered:

- Direct approach (as described in Step 3.1.): if the hydrological model is unbiased, it can be directly coupled with the hydropower model to be used for stress testing.

- Delta change approach: The hydrological model is only used to simulate the difference (delta) in the inflow series for the historical reference condition and a certain condition of climate change. This delta is then added to the observed inflow series for the historical reference period. The modified observed inflow series, representing a certain climate condition, are then input to the hydropower model.

Extreme flood events

- Flood Frequency Analyses

  If a hydrological model of daily resolution is available, the same analyses as described for the fully comprehensive approach in Step 3.1. should be applied in order to assess possible changes in flood frequencies. If only a hydrological model with monthly resolution is available, the analyses of possible changes in extreme floods must be based on a more qualitative assessment. This requires a basic understanding of the drivers for extreme floods in the region (e.g. precipitation driven or snowmelt driven) and how these drivers might change under future climate conditions. Even with monthly resolution, a hydrological model might provide some useful information to develop such understanding. If there is an indication that floods might become more frequent and extreme, some conservativism in estimation of the design flood is recommended.

- Probable Maximum Flood (PMF)

  For assessment of the PMF (if relevant), the same approach as proposed for the fully comprehensive approach in Step 3.1. may be applied. In cases where a meteorological PMP assessment cannot be conducted due to constraints in data and resources, some approximation may be useful. For instance, the Clausius-Clapeyron equation describes the water holding capacity of the atmosphere as a function of temperature. For each 1ºC change in average atmospheric temperature, it is reasonable to increase the water holding capacity of the atmosphere by about 7% and to increase the PMP in proportion. In any case, it is not recommended to explore PMP reductions for future scenarios of global warming.

Future scenarios and climate stress test

Initially, the test based on direct approach or delta analysis approach should simulate the performance for the baseline condition as well as for at least three locally-credible GCM or RCM-based climate projections (optimistic, central, pessimistic). It is recommended that these scenarios should reflect the range of the IPCC emission scenarios (e.g. RCP 4.5 (i.e. optimistic), RCP 4.5+8.5 (i.e. central), RCP 8.5 (i.e. pessimistic)). The 50th percentile change values from the CMIP5 ensemble may be used. Furthermore, a uni- or bivariate sensitivity analyses for an extended range of possible changes in mean precipitation and temperature should be conducted. It is recommended that this range should at least cover the 10th and 90th percentile change values of the above-mentioned scenarios.

Step 3.3. Limited approach

This much-simplified approach uses a uni- or bivariate sensitivity analyses of precipitation and temperature. However, in this case, the methods are driven by the limitations in the dataset that deem it inadequate to set up and calibrate a hydrological model.

Hydrological modelling

In order to assess the project performance under future climate, simplified methods such as regression models, Budyko-type water balance models and historical climate analogies can be applied.

- Regression model

  In most regions, there might be a (linear or non-linear) correlation between annual catchment precipitation and annual runoff given there is sufficient record length to determine it. Based on historical records of precipitation and streamflow, it is therefore possible to establish a regression function between these two parameters. This function can then be used to derive annual inflow series for precipitation climates that differ from the historical conditions.

Although the method cannot be used to analyse the impact of temperature changes, it allows for simple analysis of sensitivities with respect to precipitation changes.

- Budyko-type water balance models

  The Budyko framework is a widely used representation of the land water balance that describes the mean annual partitioning of precipitation into streamflow and evapotranspiration as a function of the ratio of precipitation to potential evapotranspiration. If the components of the mean annual water balance (mean annual precipitation, evapotranspiration and runoff) of a catchment are known, a Budyko function can be established. This function can then be used to estimate how mean annual streamflow would be affected if the mean annual values of potential evapotranspiration (driven by air temperature) or precipitation were to change.

  There are other limitations to the applicability of the Budyko model (e.g. it does not allow to assess seasonal changes in runoff conditions and is not accurate for regions in which snow accumulation and snowmelt play an important role). However, it might be used as an indicative method for almost any catchment type.

- Historical climate analogies

  Historical climate analogies might provide a better picture than a Budyko-type model for hydrological regimes with snowmelt influence and strong seasonality in runoff.

  The applicability of this method is contingent on the availability of at least 30 years of inflow records overlapping in the same period with indicative precipitation and temperature records. Using these indicator series of temperature and precipitation, the 10 hottest (or 10 wettest, driest, etc) years can be extracted from the flow records. For these subsamples, the mean seasonal hydrograph or the flow duration curve can be calculated. These results typically give some indication of the changes in the flow regime that can be expected under a future climate that is warmer (or wetter, drier, etc) than the baseline.

  Climate analogies allow for an assessment of seasonal changes in the flow regime. However, the method is not very flexible with respect to magnitudes of changes outside the range of the historical observations.

The combination of several methods might provide better information about the expected changes. For instance, the change in mean annual runoff could be derived from a Budyko-type model, while an indication for the expected seasonal changes could be derived from historical climate analogies. The final output would then be a modified inflow series or a modified inflow duration curve. This inflow data would then be coupled with hydropower and economic models, which would be used for assessing electricity generation and economic performance.

Extreme flood events

In catchments with very limited flow data, the design floods for historical conditions are typically derived based on empirical methods or regional flood frequency analyses. The results are subject to considerable uncertainty due to the open question related to the transferability of such functions in the future and a quantitative assessment of climate change impact is almost impossible.

Therefore, it is recommended to assess possible changes in extreme flood events and flood frequencies in a more qualitative way. This requires a basic understanding of the drivers for extreme floods in the region (e.g. precipitation driven or snowmelt driven) and how these drivers might change under future climate conditions. If there is an indication that floods might become more frequent and extreme, some conservativism in estimation of the design flood is recommended.

Climate stress test (simplified to sensitivity analyses)

In a first step, the assessment should be done for the baseline and at least one scenario considered representative for the future climate conditions (e.g. centroid of current GCM ensemble such as CMIP5).

In a second step, a sensitivity analysis should be performed covering a possible range of changes in mean annual precipitation and temperature derived from the GCM ensemble. This range might also be extended in order to identify the failure condition with respect to generation and economic performance. The sensitivity analyses might be conducted separately for temperature and precipitation (uni-variate), or by combining the two variables (bi-variate).

Step 3.4. Stakeholder engagement

The results from the stress test in either steps 3.1., 3.2. or 3.3., which present the project risks, must be shared and discussed with the relevant stakeholders. Under Phase 3, the relevant stakeholders essentially include hydropower and climate change specialists and technical services/institutions involved in hydropower generation and safety. The engagement process should provide stakeholders with the opportunity to comment on the outputs of Step 3.1. (or 3.2. or 3.3.). Relevant documentation should be shared to ensure the process is open and transparent.

Step 3.5. Risk and opportunity register update

The outcome of the climate stress test in Phase 3 is a recommendation on whether the planned or existing project is vulnerable to climate change for the performance metrics agreed during Step 1.6. and suggests the magnitude and likelihood of adaptation measures.

With the results of the stress test in Step 3.1. (or 3.2., or 3.3.), review and update the risk and opportunity register. The risk and opportunity register should show the likelihood of project risks and opportunities calculated in Phase 3, in particular steps 3.1. and 3.2., for climate change.

Phase 4

Climate risk management

Objective: To adapt the project design – and/or make the project design adaptive – to ensure it is resilient to climate changes, while remaining cost-effective and economically sensible and sound.

Outcome: Project is designated to be resilient to climate change. Develop Climate Risk Management Plan (CRMP).

This phase addresses the project's adaptation so the performance can cope with the climate risks in the vulnerable conditions identified in Phase 3. Step 4.1. will help to identify and select measures to build resilience into the project (Step 4.2.) for managing the climate risks identified in Phase 3. This phase entails several iterations between steps and involvement with Phase 3.

In the case of greenfield or rehabilitation projects, this phase will be undertaken during the final stage of a feasibility study once all of the project components have been defined.

The findings of the resilience analysis in Step 4.3. will designate whether the project is resilient. If the resilience measures are not viable to guarantee the resilience of the project and major changes have to be made (redesign), the modified project should re-enter Phase 1.

If the project is designated resilient to climate change, develop the CRMP, which integrates the refined risk and opportunity register taking into account the agreed resilience measures in Step 4.5. Finally, the assessment continues to Phase 5.

Step 4.1. Resilience measures identification

Using the results from Phase 3, identify a set of resilience adaptation measures that (alone or in combination) would enhance the project's performance to climate change. Refer to the example list of Annex C.

Considerations to take into account when identifying the resilience adaptation measures:

- Successful adaptation must be a combination of structural and functional changes combined with a high degree of collaboration across different disciplines (i.e. engineering, environmental and social), as noted in the ICOLD Bulletin on 'Global Climate Change, Dams, Reservoirs, and Related Water Resources' in 2016. Annex C provides examples of both structural and functional adaptation measures.

- Prioritise the analysis of investment required to reduce potential risk to infrastructure safety over investment needed to reduce potential risks to other strategic project objectives/ functions (e.g. generation, environment, and other uses/benefits of the projects such as irrigation water supply) in Step 4.3.

- Measures to reduce potential risks to safety should focus on plausible pessimistic scenarios. The selection of measures to reduce the risks associated with generation and other strategic project functions can be based on the outputs of the economic model for different scenarios (in addition to the scenario preferred by the stakeholders). Additional scenarios could also include a near-zero discount rate to help identify longer-term societal impacts that may extend beyond the time horizon of immediate interest to the developers.

- Adaptability should be core to all resilience measures. Due to the uncertainties inherent in current and future climate change, it is important to ensure that the resilience measures selected allow for future adaptation. These measures should not lock the project into structural or operational configurations that cannot be modified or adapted if unexpected climate scenarios materialise (e.g. the possibility of including additional spill capacity and/or flood routing capacity in the future, adding supplemental turbine(s) to the powerhouse, responding to future water needs).

- The measures need to improve project resilience while remaining cost-effective and economically acceptable.

Step 4.2. Options for modified design

Based on the selection of structural and functional measures in Step 4.1., identify the options to modify the project design in order to build resilience into the project and reduce the climate-related risks.

Each modified design will include one or a combination of the resilience (functional and/or structural) measures identified in Step 4.1. These designs will be tested for resilience in Step 4.3. The set of modified designs can range from one with minimal changes to one with more significant adjustments.

In some cases, these modified project designs can be identified using the expert judgment of the practitioners. In other cases, robust optimisation methods (discussed in Annex D) can help practitioners select promising combinations of options. In general, the range of modifications practically available will be larger for greenfield projects or those with a major rehabilitation plan than for operating projects. Key stakeholders (i.e. owners/developers) might consider the following factors in selecting several modified designs:

- Existing projects: assess whether simple structural and functional measures can be implemented to current components and operations.

- Planned projects: identify the design that is the best feasible option (given the information at the time) that balances meeting performance metrics with the potential for future modification. Perform incremental cost-benefit analyses on key project components that are being optimised.

- Future projects: assess design options that can be cost-effectively built to be flexible and that can be modified for different climate scenarios following an adaptative approach (e.g. increased storage, different sites for greenfield projects).

Step 4.3. Resilience analysis

After the identification of the resilience measures in Step 4.1. and the selection of options for the modified design in Step 4.2., it is necessary to evaluate the ability of each option to reduce the potential risks while satisfying the specified performance metrics for the future climate scenarios.

The options will need to be re-run through the models set up in Phase 3 to undertake the climate stress test. In some cases, it will prove sufficient to use a smaller number of climate scenarios (e.g. more optimistic and pessimistic case scenarios). In other cases, the full set of alternative climate projections will be necessary. The analysis should never rely on a single scenario.

To determine the most resilient project design using the results from the evaluation of the options:

- Calculate the potential loss of each modified project design in each scenario. The potential loss (or regret) of a design in any scenario is the difference between the performance of that design in that scenario and the performance of the best design for that scenario. Note that each design will have a separate value of regret for each performance measure of interest. For further information on the regret calculation refer to Annex E.

- Apply two decision criteria:
  - Minimise the maximum loss (regret): after identifying the maximum regret for each project design, this criterion suggests that the design with the smallest maximum regret is the most resilient design among the options.
  - Tolerable loss: each performance measure may have a tolerable level of regret identified and agreed with key stakeholders (e.g. it may be sufficient for a project's actual power generation to come within 10% of the best possible performance in any scenario). This criterion suggests that the design for which the regret is within this tolerable level of regret for the greatest number of scenarios is the most robust strategy. It also selects the design that performs well compared to the alternatives over the widest range of scenarios and selects a design similar to that one which would be chosen if all the scenarios were regarded as equally likely.
- Decide on the most climate-resilient project:
  - If the two criteria above suggest a similar design, the option identified in Step 4.2. is demonstrated to be resilient across a wide range of unpredictable climate change with the implementation of the measures selected in Step 4.1. for that option.
  - Otherwise, return to Step 4.1. to identify additional options to consider or conduct more extensive processes as set out in Annex D Decision Making under Uncertainty (DMU).
  - If the evaluation does not identify a resilient design during Step 4.2., the project design can either be:
    - Further adjusted, if there is an individual feature that has been shown to not meet the resilience requirements (e.g. reservoir storage volume could be increased to allow for more extreme peak flood events, or the dam can be redesigned to accept overtopping without failure for extreme floods). If this is the case, the project will re-enter the process in Phase 3.
    - Redesigned, if the overall project or components of the project fail to meet the resilience requirements (e.g. the risk of a major landslide into the reservoir may lead to the overtopping of the dam). If this is the case, the project will re-enter the process in Phase 1.
    - Deemed too risky and be abandoned in favour of an alternative (the 'do-nothing' alternative being a viable option at this point).

Step 4.4. Risk and opportunity register update

Considering the findings of Step 4.3., the risk and opportunity register should be refined and updated to include the resilience measures selected under Step 4.1. linked to the chosen resilient project.

Step 4.5. Stakeholder engagement

The results from steps 4.1., 4.2. and 4.3. should be shared and discussed with the relevant stakeholders. These relevant stakeholders include any third party who is directly or indirectly interested in the performance metrics achievements or the implementation of the climate resilience management plan. The engagement process should provide stakeholders with the opportunity to comment on the CRMP. Relevant documentation should be shared to ensure the process is open and transparent.

If the stakeholder engagement process identifies actual issues that had not been anticipated in the CRMP, the developer should consider modifying the plan.

Step 4.6. Climate Risk Management Plan

The CRMP should include the risk and opportunity register including the performance metrics and the resilience measures. Each of the resilience measures should also be described in detail, including a detailed technical description, a description of the preparation steps such as additional studies, implementation arrangements, direct costs and externalities, timeline for implementation, and third parties involved. The responsibility for each of these resilience measures must be clearly defined along with a timeline for the proposed action.

Seek appropriate senior-level acceptance and sign-off on the budget to implement the CRMP. Following agreement of budget/funding, implement the plan into the project process.

The CRMP should include or refer to O&M processes identified to cover the implementation of resilience measures, as well as the Emergency Action Plan (EAP) if it already exists.

The Monitoring, Evaluation and Reporting (MER) plan will monitor the successful and timely implementation of the CRMP.

Phase 5

Monitoring, evaluation and reporting

Objective: To track how resilient the project is in operation and to allow the climate resilience management plan to be monitored, reported on, evaluated and updated.

Outcome: Monitoring, Evaluation and Reporting (MER) plan.

The overall process is an adaptive management feedback loop. This final phase is therefore included to track how resilient the project is in operation and to allow the climate risk management plan to be monitored, reported on, evaluated and updated.

Key to this phase is agreeing a set of 'triggers' in order to review and update the climate risk management plan, keeping in mind that climate resilience performance must, by nature, be evaluated over a relatively long time scale given the nature of climate variability: a sequence of one or two more or less 'bad years' (in terms of inflows for hydro generation or in terms of flood occurrence for dam safety) does not systematically ask for a deep review of design options or resilience measures.

The MER plan should be integrated with the climate risk management plan and connected to the O&M plan. If the project enters Phase 5 directly from Phase 1, the MER plan should be integrated with the O&M plan, linked to regular reporting intervals and based on the prioritised measures, including assignment of ownership and reporting responsibility of actions.

Step 5.1. Climate resilience monitoring plan

The climate resilience monitoring plan should be connected to the O&M plan for the project. This can either be reproduced within the Climate Risk Management Plan or referenced within the relevant section of the O&M plan.

For each climate-influenced risk of the risk register, set out:

- How resilience measures that help maintain the risk at an acceptable level will be monitored and reported, if any additional or new data collection or process needs to be set up.
- How lessons learned from experienced events will be captured.
- When the monitoring and reporting will take place to feed in to the evaluation process.
- Who is responsible for monitoring, reporting and evaluating each action.
- The dataset (type and acquisition frequency) that needs to be regularly collected for future climate risk assessments and to ensure that responsibilities are assigned and budgets available for their collection: data covers hydro-meteorological parameters in the catchment, but also natural hazards parameters (e.g. in glacierised mountain regions). This may include data generated internally or acquired from external sources. The dataset has to be consistent with the data used during the previous climate risk assessment.

- The internal or external resources of equipment and facilities needed to acquire this data must be identified. Engagement and support of local and regional authorities identified in Requirement 3 may sometimes be fundamental to implementing the monitoring.
- The resources/effort agreed to undertake the activities of Phase 5.

Step 5.2. Evaluation and reassessment of climate risks

An agreed set of requirements will trigger a re-analysis and update of the climate risk management plan. In any case, like other assessments such as the regulatory safety review, a time step of 10 years should be the limit for a full reassessment (i.e. return to Phase 1).

Suggested triggers for a more in-depth reassessment can be considered in terms of:

- Significant long-term changes to the climate change prospect or trends, such as new scientific evidence (e.g. new GCM projections).
- New competing water users, regulatory changes that affect water use or availability, etc, that might or might not be climate-related.
- A new and unexpected event or sequence of events that relate to climate or natural hazards (e.g. a major climatic event that may impact on initial assumptions). However, over-reaction must be avoided and each untypical event must be appraised. A significant event may remain in the expected acceptable variability.

Based on the analysis of key factors and the triggers agreed above, re-run the climate stress test with updated information identified in Step 5.1. If new resilience measures need to be considered, undertake Phase 4.

Step 5.3. Stakeholder engagement

Undertake a formal review and evaluation of progress. Review the monitoring and reporting results, lessons learned and evaluation findings. Communicate high level findings of the lessons learned to relevant stakeholders as appropriate.

Revise, add to or identify new resilience actions (and support mechanisms) and any new monitoring procedures required. Any update to the MER plan in the CRMP should be shared with all relevant stakeholders.

Notes

1. International Hydropower Association (IHA), 2018. Hydropower Sustainability Guidelines on Good International Industry Practice. London.

2. ICOLD Technical Committee on Climate Change, 2016. Bulletin 169 Global Climate Change, Dams, Reservoirs, and Related Water Resources. ICOLD.

3. World Meteorological Organization, 2019. http://www.wmo.int/pages/prog/wcp/ccl/faqs.php

4. Refer to the World Bank's Climate and Disaster Risk Screening Tool for this assessment. The tool provides a systematic way to undertake due diligence and flag potential risks for projects in the energy sector. Access http://climatescreeningtools.worldbank.org/energy/energy-welcome

5. The World Bank Group, 2019. Climate Change Knowledge Portal. http://sdwebx.worldbank.org/climateportal/

6. U.S National Centre for Atmospheric Research, 2019. Climate Data Guide. https://climatedataguide.ucar.edu/climate-data

7. Same as 5.

8. Osborn T.J., C.J. Wallace, I.C. Harris and T.M. Melvin. 2016. Pattern scaling using ClimGen: monthly-resolution future climate scenarios including changes in the variability of precipitation. Climatic Change, 134, 353-369. https://dx.doi.org/10.1007/s10584-015-1509-9

9. University of East Anglia. 2018. Climate Projections & Observations. https://crudata.uea.ac.uk/~timo/climgen/national/web/about.htm

10. Intergovernmental Panel on Climate Change, 2019. http://www.ipcc-data.org/

11. When weather generators are used to systematically test the climate sensitivity of impact models, systematic shifts are applied to produce new sequences of weather variables (for instance precipitation) that exhibit a wide range of change in their characteristics (such as average amount, frequency, intensity, and duration). In the context of a climate stress test, a stochastic weather generator can be built for a region of interest and used to generate several scenarios of daily climate within which a water resources system can be tested. The flexibility of stochastic weather generators enables many climate permutations to be generated, each of which can exhibit a different type of climate alteration that the analyst may be interested in. Note that the permutations created by the weather generator are not dependent on any climate projections at this point in the analysis, thereby allowing a wide range of possible future climates to be generated while avoiding biases propagated from the projections. However, the particular permutations generated can be informed by available projections to ensure that they more than encompass the range of GCM projections.

12. The term Decision Making Under Deep Uncertainty (DMDU) is also used for these approaches, in which the phrase "deep uncertainty" denotes probabilities such as the return period for extreme flooding that are known imprecisely, if at all. This contrasts with situations of well-characterised uncertainty in which the probabilities are known with high confidence.

13. See, for instance, New Zealand's recent sea level rise guidance and California's Climate Safe Infrastructure Guidance. http://www.mfe.govt.nz/publications/climate-change/coastal-hazards-and-climate-change-guidance-local-government

14. See, for instance, the 2018 workshop of the Society for Decision Making Under Deep Uncertainty. www.deepuncertainty.org

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Annex A

Climate stressors

Consequences of climate change and climate-induced natural disasters should be considered with respect to direct climatic stressors which affect the specific hydropower system itself, typically during an extreme event, and indirect climatic stressors, which affect the hydropower system by first gradually changing everyday processes in the wider environment and river basin. Climatic variables include temperature, precipitation and wind (comprising cyclones, hurricanes and storms). Examples of major impacts from various climatic stressors on hydropower projects are summarised in Table 5.

Table 5. Examples of climate stressors on hydropower projects.

Climatic variable	Impacts or stressors on project component	Indicators	Timescales
Energy generation			
Precipitation and streamflow	• Hourly generation levels (shift from evening to mid-day peak) and seasonal levels (change from winter to summer peak)	• Change in grid requirements resulting in changes to power purchase agreements (PPA) or plant operations	• Gradual, long-term
	• System load factor changes (ratio of peak MW to average)	• Energy output	• Gradual, long-term
	• Impacts on other technologies (reduced thermal due to cooling water temperature/ availability, output of renewables)		
	• Changes in downstream water releases and lower minimum environmental flows	• Damages to fish habitat • Daily flooding	• Gradual, long-term
Access roads and camps			
Precipitation and streamflow	• Heavy downpours damaging unsurfaced roads	• Damage to roads • Increased surface water on roads	• Extreme, sudden
	• Increased flows in culverts and road/ camp drainage	• Flooding around culverts/crossings and camps	• Gradual, long-term

Climatic variable	Impacts or stressors on project component	Indicators	Timescales
	• Increased debris from higher or flashy surface runoff	• Blocking of culverts, intakes and waterways	
	• Increased risk of slope instability (surface water triggered failures and ground water induced failures)	• Slope movement from monitoring • Surface failures causing road damage (rockfalls, mudslides)	• Extreme, sudden
	• Increased/decreased stream runoff resulting in additional/reduced river crossings	• Surface runoff damaging roads at locations where no culvert/crossing was allowed for	
Temperature	• Thinner ice cover and permafrost melting	• Degradation of roads due to the melting of foundations • Ice cover insufficient to walk/drive on lakes and access specific areas	• Gradual, long-term
Dams and appurtenant works (including spillway, intake structure and sediment handling structures)			
Precipitation and streamflow	• Increased sediment load resulting in loss of storage or additional flushing frequency (if designed for flushing)	• Increased/decreased sediment loads blocking gates • Corrosion of gates	• Gradual, long-term
	• Spillway is of insufficient size to pass floods leading to dam safety issues	• Damage to spillway • Overtopping of dam in high flow events (greater likelihood of more frequent emergency discharges) • Requirement to draw down reservoir prior to high flow events	• Extreme, sudden
	• Increased risk of slope instability (surface water triggered failures and ground water induced failures)	• Slope movement from monitoring • Surface failures causing damage (rockfalls, mudslides)	• Extreme, sudden
	• Changed environmental flows (for fish, water quality, navigation)	• Ecological changes downstream	• Gradual, long-term

Climatic variable	Impacts or stressors on project component	Indicators	Timescales
	• Changed flows for fish passage system(s)	• Ecological changes upstream	• Gradual, long-term
	• Erosion at toe of dam due to increased spillway discharge	• Erosion of plunge pool at dam toe	• Gradual, long-term
Reservoir			
Precipitation and streamflow	• Reservoir slope instability causing landslides into reservoir	• Slope movement from monitoring • Surface failures causing damage (rockfalls, mudslides) • Failures into reservoir causing displacement waves	• Extreme, sudden
	• Glacial hazards (e.g. GLOFs) leading to safety issues with dam	• Major high flow events	• Extreme, sudden
	• Increased flood flow resulting in variable reservoir inflow	• Operating regime of scheme is not as planned • High/lower reservoir levels	
	• Increased trash and vegetation in reservoir from increased runoff	• Increased volume of trash in reservoir	• Gradual, long-term
	• Increased water temperature (fouling, oxygen content, stagnation)	• Unexpected variations in reservoir temperature • Reduced oxygen levels • Stagnation and fish kills	• Gradual, long-term
	• Increased/decreased sediment loads impacting operating regime of reservoir	• Corrosion to gates, flushing facilities and intakes	• Gradual, long-term
	• Additional floating vegetation/ algae potentially clogging intakes	• Increased surface vegetation and algae	• Gradual, long-term
Temperature	• Increased evaporation losses (absence of ice cover, drier air), leading to reduced water for generation	• Increased reservoir losses • Reduced energy output	• Gradual, long-term

Climatic variable	Impacts or stressors on project component	Indicators	Timescales
	• Increased water temperature (fouling, oxygen content, stagnation and fish kills)	• Higher/lower water temperatures than expected	• Gradual, long-term
Powerhouse, tailrace and switchyard			
Precipitation and streamflow	• Flooding of powerhouse due to increased fluvial flow	• Flooding of powerhouse or higher flood levels than in design	• Extreme, sudden
	• Flooding of powerhouse from direct precipitation	• Flooding of powerhouse or higher flood levels than in design	• Extreme, sudden
	• Increased risk of slope instability (surface water triggered failures and ground water induced failures)	• Slope movement from monitoring • Surface failures causing damage (rockfalls, mudslides)	• Extreme, sudden
	• Higher/lower flows available for increased/decreased installed capacity	• Energy output different to that planned/ required for financing	• Gradual, long-term
Temperature	• Increased snow causing structural issues in powerhouse	• Damage due to snow/ice loading on roof; increased frequency of ice storms affecting T/Lines	• Extreme, sudden
	• Increased snow causing access issues to powerhouse and switchyard	• Inability to access areas due to snow/ice	
	• Increased/decreased temperature within powerhouse causing problems for people and equipment	• Equipment failures due to heat • Mould, condensation in powerhouse	• Gradual, long-term
	• Increased water temperatures causing problems for alternators cooled in closed circuits	• Insufficient alternator cooling, leading to service disruption	• Gradual, long-term
	• Material durability issues and expansion/ contraction causing cracking, leading to leakage, instability or aesthetic issues	• Damage to concrete (e.g. cracking)	• Gradual, long-term

Climatic variable	Impacts or stressors on project component	Indicators	Timescales
Waterways (e.g. delivery canals)			
Precipitation and streamflow	• Increased flows through waterways	• Spilling from waterways • Damage to waterway structures and gates	• Extreme, sudden
	• Increased risk of slope instability (surface water triggered failures and ground water induced failures)	• Slope movement from monitoring • Surface failures causing damage (rockfalls, mudslides)	• Extreme, sudden
	• Increased sediment deposition leading to diminished flows and loss of storage and hence depleted peaking energy in storage plants	• Sediment deposition	• Gradual, long-term
Temperature	• Material durability issues and expansion/contraction causing cracking, leading to leakage, instability or aesthetic issues	• Damage to concrete (e.g. cracking)	• Gradual, long-term
Electromechanical equipment			
Precipitation and streamflow	• Varied flows result in different sediment loads which can cause turbine erosion	• Corrosion/damage to turbines • Increased maintenance requirements • Reduced efficiency of Electromechanical equipment	• Gradual, long-term
Temperature	• Cooling water (sizing, blockage due to vegetation/algae)	• Damage to turbines • Increased maintenance requirements • Reduced efficiency of Electromechanical equipment	• Gradual, long-term
	• Corrosion resistance (more aggressive at high temperatures)	• Corrosion/damage to turbines • Increased maintenance requirements • Reduced efficiency of Electromechanical equipment	• Gradual, long-term

Climatic variable	Impacts or stressors on project component	Indicators	Timescales
	• Increased operating temperatures (impacts on serviceability, durability, ratings)	• Reduced ratings, durability and increased maintenance requirements	• Gradual, long-term
Transmission lines			
Precipitation and streamflow	• Increased risk of slope instability (surface water triggered failures and ground water induced failures)	• Slope movement from monitoring • Surface failures causing damage (rockfalls, mudslides)	• Extreme, sudden
	• Increased flooding along transmission line route	• Damage to transmission towers • Difficulty accessing route for maintenance or monitoring	• Extreme, sudden
Temperature	• Increased temperature effects on conductor capacity	• Conductor efficiency drops and durability decreases	• Gradual, long-term
	• Lightning protection (changed risk)	• Damage due to lightning	• Extreme, sudden
	• Atmospheric changes affecting solar radiation/solar flares		
	• Increased dust on insulators	• Problems with insulators due to dust	• Gradual, long-term
	• Increased frequency, distribution and severity of bush fires damaging transmission lines and substations		
	• Warmer air temperature	• Increased frequency of right-of-way maintenance since vegetation grows faster; ground clearance distance reduced by increased cable length	• Gradual, long-term
	• Permafrost melting	• Stability and anchoring become problematic	• Gradual, long-term

Annex B

Risk and opportunity register

Table 6. Example of risk and opportunity register

Climate stressor	Threat/ opportunity	Time scale	Potential loss/ gain	Likelihood	Risk/ opportunity level
E.g. increased streamflow	Description of the threat event or the opportunity	E.g. scale 1-3	E.g. scale 1-3	E.g. scale 1-3	E.g. negligible, low, medium, high, very high

The development and update of the project risks and opportunities register is an integral part of the climate risk assessment. The risk and opportunity register is created in Step 1.5. to evaluate in a qualitative way whether the project needs to carry out a climate risk assessment. As the assessment develops, the risk and opportunity register will become more in-depth in terms of the level of detail considered and the accuracy of the likelihood, consequence and overall risk/opportunity.

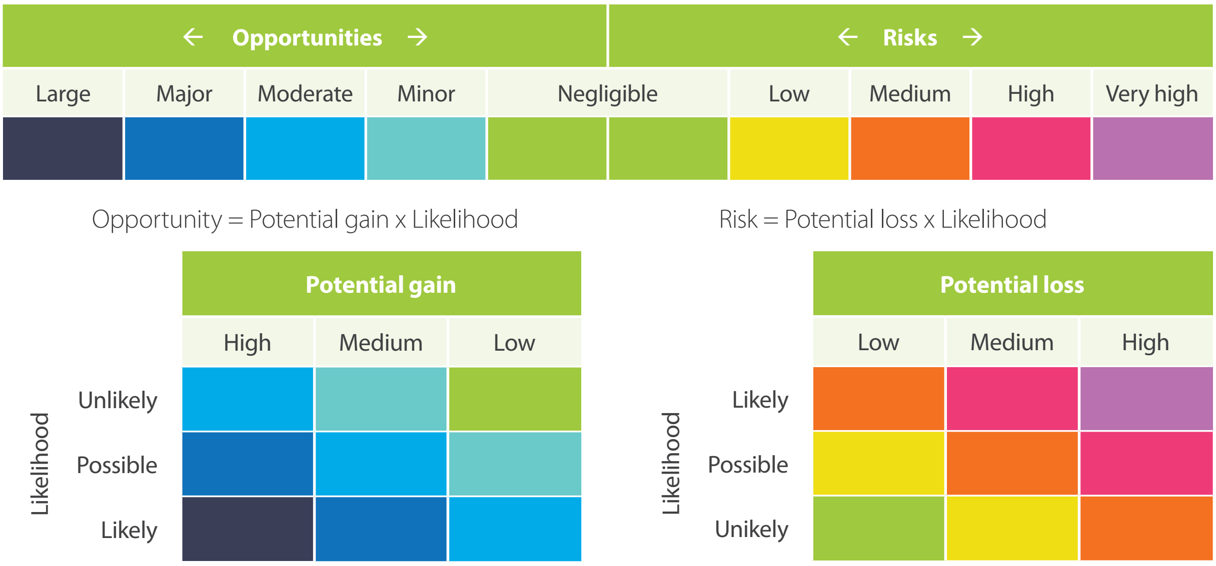
An example of a risk and opportunity register is shown in Table 6. The register needs to include the description of the threat/opportunity, the impact of the time scale, the potential loss/gain and likelihood in order to estimate the risks/opportunity level.

A threat is a circumstance, action or event that might exploit a vulnerability with the potential to adversely impact an asset or a system. A vulnerability is the degree to which a system is susceptible to or unable to cope with adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.

Risk (or opportunity) is defined for a system or function as the combination of the potential loss (or gain) and the likelihood of the climate event.

Risk (or opportunity) =
Potential loss (or gain) x Likelihood

Table 7. Example of risk/opportunity assessment scale scores.



← Opportunities →						← Risks →			
Large	Major	Moderate	Minor	Negligible		Low	Medium	High	Very high
⬛	🟦	🔵	🟢	🟩	🟩	🟨	🟧	🟥	🟪

Opportunity = Potential gain x Likelihood

		Potential gain		
		High	Medium	Low
Likelihood	Unlikely	🔵	🟢	🟩
	Possible	🟦	🔵	🟢
	Likely	⬛	🟦	🔵

Risk = Potential loss x Likelihood

		Potential loss		
		Low	Medium	High
Likelihood	Likely	🟧	🟥	🟪
	Possible	🟨	🟧	🟥
	Unikely	🟩	🟨	🟧

A scoring system for the risk/opportunity assessment process will need to be agreed between the user of the guide and developer or asset owner. It can be a qualitative or quantitative scoring system. An example risk assessment scale score is presented in Table 7.

Risk and opportunity registers are not unique to the climate risk assessment, but they are a fundamental part of any hydropower design process. In the case of greenfield projects, the climate risk assessment should build on the existing project risk and opportunity register by considering additional climate risks/opportunities and by considering climate as a 'threat multiplier' on the risks/opportunities already identified in the project register. For the latter, additional columns can be added to the risks encountered during the technical and ESIA stages (as shown in Table 8).

As a good practice, the minimum (MIN), most likely (ML) and maximum (MAX) cost impact from each risk/opportunity can be considered and a Monte Carlo analysis can be utilised to produce distribution curves of the potential costs of project risks versus the probability of occurrence.

Table 8. Example of an incremental risk and opportunity register for a greenfield project.

	Technical and ES impact assessment								**Incremental climate impact assessment**							
Threat/ opportunity	Likelihood (1-5)	Impact cost (1-5)	Impact time (1-5)	Score =	Likelihood (%)	MIN cost impact ($000)	ML cost impact ($000)	MAX cost impact ($000)	Likelihood (1-5)	Impact cost (1-5)	Impact time (1-5)	Score =	Likelihood (%)	MIN cost impact ($000)	ML cost impact ($000)	MAX cost impact ($000)
Description																

Annex C

Examples of structural and functional adaptation measures

In Phase 4, we should incorporate adaptation measures to build climate resilience into the system. Examples of structural and functional adaptation measures are given in Table 9.

Table 9. Examples of structural and functional adaptation measures for new and existing hydropower projects

Climatic variable	Impacts on project component	Potential resilience adaptation measures
STRUCTURAL ADAPTATION MEASURES		
Access roads and camps		
Temperature	Freeze-thaw damage road construction	• Additional construction joints • Suitable pavement materials for temperature variations
	High temperatures damage road construction	• Additional construction joints • Suitable pavement materials for temperature variations
	Increased dust on temporary or unsurfaced access roads	• Road surfacing • Increased dust suppression (sprinklers)
	Decreased ice thickness on lakes, marshes, peat bogs, shortening periods during which ice bridges can be used	• Alternative access roads to be built • Remote sensing/control of parameters/activities that used to be measured/implemented on site
	Melting of permafrost and alternations to road, foundations	• Amend road design with more consideration of geotechnical conditions under positive ground temperature
Precipitation and streamflow	Heavy downpours damaging unsurfaced roads	• Increased drainage • Road surfacing/gravelling (revised material specification) • Road design amendments (e.g. additional camber) • Increased provisions and allowances for O&M

Climatic variable	Impacts on project component	Potential resilience adaptation measures
	Increased flows in culverts and road/camp drainage	• Culvert and drainage sizing revised for hydrological uncertainty, in particular a potential increase in the runoff for the design criteria that have been considered appropriate for the structure; for example, it may be decided that it is appropriate to design the culverts for a larger event once the climate change impacts on hydrological modelling are determined
	Increased debris from higher or flashy surface runoff	• Debris screens to be added to drainage and culverts • Increased maintenance
	Increased risk of slope instability (surface water triggered failures and ground water induced failures)	• Increased landslide hazard assessments (mapping) • Additional slope protection • Additional crossing designed • More robust assessment of road alignment
	Increased/decreased stream runoff resulting in additional/reduced river crossings	• Revised route selection • Additional crossing designed • More robust assessment of road alignment
	Camp location selection more challenging (higher risk uncertainty) (e.g. historical one in 25-year events may not be accurate looking forward)	• More robust assessment of camp location (depending on construction duration)
	Low flow periods may be more severe, entailing the rejection of treated water from camps due to insufficient dissolution	
River diversion and works		
Precipitation and streamflow	Increased flashy or sustained high flow events	• Design which uses the most recent hydrological data rather than historical data • For concrete dams, accepting and organising overtopping of construction work enables significant savings in diversion tunnel works
	Lack of low flow period for riverbed construction	• Construction planning for minimal low flow period (including selection of river diversion works e.g. a tunnel may be preferable)
Dam and appurtenant works (including spillway, intake structure and sediment handling structures)		
Precipitation and streamflow	Increased sediment load resulting in loss of storage or additional flushing frequency (if designed for flushing)	• Additional flushing and sediment management facilities • Change in operation methodology • Incorporation of catchment erosion control plan • Raising of dam crest to increase live storage • Development of upstream sediment control facilities

Climatic variable	Impacts on project component	Potential resilience adaptation measures
	Spillway is of insufficient size to pass floods leading to safety issues for dam (e.g. for adaptation of existing projects)	• Increase spillway capacity • Additional spillway/fuse gates • Use of labyrinth or piano key weirs • Rubber dams • Reassessment of dam type to allow overtopping (i.e. a concrete dam) • Increased freeboard or allowance for flood rise • Addition of upstream parapet/wave wall on dam crest
	Increased risk of slope instability (surface water triggered failures and ground water induced failures) (e.g. for adaptation of existing projects)	• Additional slope protection and stabilisation measures • Slope stability monitoring/surveying • Reassessment of dam location or alignment
	Additional loading from snow/ice/wind on dam structure and gates	• Revised load conditions (wind, snow, rain) in design
	Changed environmental flows (for fish, water quality, navigation)	• Design environmental flow capacity with potential for varying discharge rates • Design the environmental flow system so that it can be adapted in the future if ecological flow requirements change
	Changed flows for fish passage system(s)	• Design fish passage system(s) with potential for varying discharge rates • Consider climate change when designing fish passage system(s) • Design the fish passage system(s) so that it can be adapted in the future if ecological flow requirements change
	Erosion at toe of dam due to increased spillway discharge	• Relocation of spillway to ensure floods are discharged downstream of powerhouse (e.g. into a secondary channel or by extending the spillway beyond a powerhouse at the toe of the dam) • Increased energy dissipation from spillway • Increased stilling basin capacity and protection
Temperature	Material expansion/contraction causing cracking, leading to leakage or instability	• Additional monoliths and/or construction joints • New concrete mix designs which are more resilient to temperature variations • Change of dam type/choice of construction materials • Dam concrete temperature control by pre- or post-cooling

Climatic variable	Impacts on project component	Potential resilience adaptation measures
	Construction using certain materials (e.g. concrete placing or dam clay core) cannot take place in extreme temperatures	• Construction planning to take into account extreme temperature variations, which may require additional measures during construction (e.g. ice for concrete construction) or revised construction scheduling
Wind	Increased wave height and freeboard requirement for dams	• Ensure freeboard calculations account for potential increases in wind loading
	Increased wind loading on structures (buildings, transmission towers, etc)	• Ensure design for wind loading account for potential increases in wind loading
Precipitation and streamflow	Reservoir slope instability causing landslides and trees to fall into reservoir	• Detailed reservoir rim stability assessment leading to slope stabilisation in at risk areas
	Glacial hazards (e.g. GLOFs) leading to dam safety issues	• Glacial monitoring leading to operational changes • Controlled glacial reservoir breach • Change of dam type to allow overtopping
	Change of river regime with reduced base flow and increased floods	• Increased spillway capacity to allow increased flow • Consider changing operating methodology to capture increased flood in storage projects • Incorporation of provisions for future increase of the storage capacity by dam and FSL raising
	Increased waste material and vegetation in reservoir from increased runoff	• Additional trash rakes, types of trash screens and frequency of trash removal or automation, or a more robust system design
	Increased/decreased sediment loads impacting operating regime of reservoir	• Additional flushing and sediment management facilities e.g. increased temporary storage for sediment where the reservoir is being used as a desander • Change in operation methodology • Allow excavation of coarse and sand construction material by locals at reservoir tail • Additional dredging
	Additional floating vegetation/ algae potentially clogging intakes	• Consider adding overtopping facility for reservoir surface cleaning • Addition of intake trash rack rake equipment
Temperature	Increased snow causing structural issues in powerhouse	• Account for losses in power energy modelling • Floating solar/reservoir surface coverage
	Water temperature (fouling, oxygen content, stagnation and fish kills)	• Operating and maintenance monitoring

Climatic variable	Impacts on project component	Potential resilience adaptation measures
Air composition	Increased CO_2 in atmosphere stimulates plant growth in reservoir with negative impacts on intakes	• Intake design with suitable track racks/ rakes and consideration of O&M
Irradiance	Increases on reservoir water temperature	
Powerhouse, tailrace and switchyard		
Precipitation and streamflow	Flooding of powerhouse due to increased fluvial flow	• Increased flood defences for powerhouse • Relocation of powerhouse to higher ground • Surface powerhouse to be relocated underground to improve resilience to fluvial flooding • Relocation of spillway to ensure floods are discharged downstream of powerhouse (e.g. into a secondary channel or by extending the spillway beyond a powerhouse at the toe of the dam)
	Flooding of powerhouse from direct precipitation	• Increased drainage provision in and around powerhouse)
	Increased risk of slope instability (surface water triggered failures and ground water induced failures)	• Additional slope protection and stabilisation measures • Slope stability monitoring/surveying • Reassessment of powerhouse location or alignment
	Higher/lower flows available for increased/decreased installed capacity	• Increased powerhouse civil works to be adaptable for future additions of electromechanical equipment (e.g. space in powerhouse for additional turbines and generators) • Maximum capacity of the tailrace to be increased to allow for potential higher discharges
Temperature	Increased snow causing structural issues with powerhouse	• Structural design to take into account potential additional snow loading
	Increased snow causing access issues to powerhouse and switchyard	• Access to powerhouse (above snow pack level) to be allowed for in design
Temperature	Increased/decreased temperature within powerhouse causing problems for people and equipment	• Air-conditioning/heating requirements, insulation, ventilation (natural, mechanical) • Moisture control (mould, condensation, damp-proofing)
	Increased/decreased temperature causing problems with concrete placement during construction of powerhouse	• Additional construction joints • New concrete mix designs which are more resilient to temperature variations • Change of construction materials

Climatic variable	Impacts on project component	Potential resilience adaptation measures
	Increased water temperatures causing problems for alternators cooled in closed circuits	• Cooling system to be redesigned and possibly rebuilt or modified
	Material durability issues and expansion/contraction causing cracking, leading to leakage, instability or aesthetic issues	• Additional monoliths and/or construction joints • Change of concrete mix designs to be more resilient to temperature variations • Change of construction materials
Waterways (e.g. delivery canals)		
Precipitation and streamflow	Increased flows through waterways	• Slope movement from monitoring • Surface failures causing damage (rockfalls, mudslides)
	Increased risk of slope instability (surface water triggered failures and ground water induced failures)	• Additional slope protection and stabilisation measures • Slope stability monitoring/surveying • Reassessment of waterways location or alignment
	Increased sediment deposition leading to diminished flows	• Inclusion of desander basins • Additional slope protection measures • Slope stability monitoring/surveying
Temperature	Material durability issues and expansion/contraction causing cracking, leading to leakage, instability or aesthetic issues	• Additional monoliths and/or construction joints • New concrete mix designs which are more resilient to temperature variations • Change of construction materials
Electromechanical equipment		
Precipitation and streamflow	Increased flows to be passed through turbines	• Installation of variable speed turbines or turbines with higher efficiency for a wide range of discharges
	Varied flows result in different sediment loads which can cause turbine erosion	• Installation of corrosive resistant turbine blades
Temperature	Cooling water (sizing, blockage due to vegetation/algae)	• Design for increased uncertainty
	Corrosion resistance (more aggressive at high temperatures)	• Installation of corrosive resistant turbine blades
	Operating temperatures (impacts on serviceability, durability, ratings)	• Design for increased uncertainty

Climatic variable	Impacts on project component	Potential resilience adaptation measures
Transmission lines		
Precipitation and streamflow	Increased risk of slope instability (surface water triggered failures and ground water induced failures)	• Additional slope protection and stabilisation measures • Slope stability monitoring/surveying • Reassessment of transmission tower location and line alignment • Design transmission tower foundations for greater stability uncertainty
	Flooding along transmission line route	• Route selection (avoid flood plains, steep slopes)
Temperature	Temperature effects on conductor capacity	• Amendment of conductor specifications to ensure they are more resilient for a range of temperatures • Thermal effects on conductor loads
	Increased snow/ice loads on towers and conductors	• Design towers to take into account higher snow/ice loading
	Lightning protection (changed risk)	• Ensure transmission towers are designed for lightning risk
	Atmospheric changes affecting solar radiation/solar flares	
	Increased dust on insulators	• Design protection for insulators
	Increased frequency, distribution and severity of bush fires damaging transmission lines and substations	
	Ground clearance distance reduced by increased cable length	• Increased distance to the ground
	Problematic stability and anchoring in the face of melting permafrost	• Alternative design with foundation not relying on permafrost

Climatic variable	Impacts on project component	Potential resilience adaptation measures
FUNCTIONAL ADAPTATION MEASURES		
Seasonal and weekly storage		
Change of river regime with increased floods and reduced base flow	Increase or decrease in storage requirement	• Plan for revised optimal minimum operating level • Lowering of the power intake • Prepare provisions for future dam raising and increased Full Supply Level
		• Conversion of free overflow spillway into gated spillway • Addition of fuse gates to free overflow spillway • Changes to operating rules such as revised reservoir level limits in order to provide an increased flood storage buffer
Flood control		
Increased flood peak discharge	Increased flood evacuation capacity	• Revision of monthly reservoir operating rule curves • For concrete dams only, dam crest overtopping with provisions for dam toe erosion protection should be considered for extreme cases • Restriction of the development of land within the zones susceptible to flooding • Protection or removal of vulnerable areas • Establishment or revision of an Early Warning System
Sediment control		
Change in sediment load as a result of change in flow regime	Loss of active storage and/or greater generating outages	• Increased temporary storage provision • Increased and/or greater or more efficient sediment removal facilities • Sediment bypass tunnels/facilities (using surplus or part of the water to carry the sediment past the intake areas) • Use more resilient turbines

Climatic variable	Impacts on project component	Potential resilience adaptation measures
Flexible multi-purpose uses		
General climate change concerns	Changes to water users nor directly associated with hydropower functions	• Carrying out studies directed at identifying the impacts of climate change upon the various users of water within a watershed • Modification to legal agreements between various governments, stakeholders and other identities that have an impact upon the operation of the watershed • Improvement to technologies that are used to coordinate the interaction of various hydro projects as well as the global operation of complexes involving several watersheds • Better coordination of the operation of the project with other water uses in the watershed
		• Promotion of educational efforts designed to inform citizens of the impacts of climate change, with the hope of finding adaptive measures that would compensate for the impacts and reduce negative impact on hydropower • Modification to rules that have an influence upon recreation, irrigation, water supply and industrial water abstraction
Energy demand		
Temperature	Daily demand levels (shift from evening to mid-day peak) and seasonal demand levels (change from winter to summer peak)	• Reassessment of the type of scheme (base load/peaking and run-of-river/storage) • Reassessment of the need to increase installed capacity
Energy market		
General climate change concerns	Change in the value of produced electricity	• Monitoring of market trends and regular reassessment
Transmission lines		
Temperature	Vegetation growing faster in the Right-of-Way	• Increased frequency of right-of-way maintenance
	System load factor changes (ratio of peak MW to average)	• Reassessment of the type of scheme (base load/peaking and run-of-river/storage)
	Impacts on other technologies (reduced thermal due to cooling water temperature/availability, output of renewables)	• Reassessment of the type of scheme (base load/peaking and run-of-river/storage)

Climatic variable	Impacts on project component	Potential resilience adaptation measures
Precipitation and streamflow	Increased or decreased energy	• Development or improvement of hydrological forecasting tools including the development and application of appropriate measures to deal with extreme hydrological events, specifically with a view towards estimating power energy modelling
Grid support		
General climate change concerns	Changed generation mix – replacement of fossil fuels by renewables	• Increased focus for hydro on ancillary services for integration of other renewable generation • Greater storage needed to backup intermittent generation • Increased mechanical inertia to replace decommissioned thermal plants
	Increased behind-the-meter generation	• Dispatchability becomes more important as quantity of uncontrolled generation increases
	Change from fossil fuels to electricity for space heating	• New hydro generation needed to meet increasing energy demand
	Change from fossil fuels to electricity for transport	• New hydro generation needed to meet increasing energy demand
Operation of hydropower assets		
		• Development of improved technologies to evaluate the performance of projects and to identify ways of operating them under modified climatic conditions • Creation of regulatory bodies that are mandated to develop and apply improved operating strategies

Annex D

Decision Making under Uncertainty (DMU)

The planet is warming, and quickly. That is not uncertain. What is uncertain, and hugely so, is the impact the warming will have on the climatologic and hydrologic processes that directly influence hydropower performance. Leading scientific bodies, international lenders such as the World Bank Group and organisations such as the Intergovernmental Panel on Climate Change recommend addressing climate change as a risk management challenge, which includes recognising and assessing potential risks (as well as potential opportunities) posed by changing climate conditions, such as average precipitation or the frequency of extreme drought, and then developing and applying tailored approaches to help reduce or minimise any associated negative impacts.

Hydropower engineers, planners, and managers are no strangers to uncertainty and risk management. Current industry guidelines and practices employ approaches based on probabilistic risk and cost-benefit analysis as well as scenario analysis. The former generally assume the availability of well-characterised probability distributions while the latter generally do not use probabilistic information. Engineers stress test their designs to identify potential vulnerabilities. They also have many options for managing uncertainty, including safety margins, operational rules (such as demand restrictions) and investment in infrastructure which is relatively insensitive to climate variability (e.g. storage vs. run-of-river dams).

Problems arise when well-characterised probabilistic information is not available. Probabilities (of seasonal temperature, extreme precipitation or river stage, for example) are developed by fitting distributions to historical observations and are useful for analysing future risks when the past is assumed to be a reasonable approximation for the future. A rapidly changing climate means that the probabilities developed using historical observations may no longer be applicable for anticipation of future conditions. This has been described as the death of stationarity (Milly et al., 2008).

In response, a broader suite of approaches, methods and techniques designed to help and guide decision makers through DMU are being developed.[12] These approaches combine the best features of probabilistic risk and cost-benefit analysis with those of scenario analysis. They are bottom-up and robustness-based. Bottom-up planning paradigms emphasise analysis tailored to the needs of the local project stakeholders (as opposed to top-down analysis developed for the generic case) and robustness-based planning paradigms value the ability to perform well across a wide range of unpredictable possible futures over the ability to perform optimally in an expected future state. DMU approaches are also multi-objective in that they seek strategies that perform well when evaluated by a variety of metrics – such as cost, reliability, worst-case return on investment, environmental impact – rather than aggregating all metrics into a single, often monetary measure.

This paradigm shift is needed for several reasons. First, many uncertainties facing hydropower development have become larger or more difficult to characterise. Climate change is a salient example, but in many cases economic, technological, social, and political uncertainties may be even larger. In these cases, there may be disagreement about how to best describe or model the uncertainty using traditional approaches. Second, whereas in the past decision makers benefitted from greater governmental powers, manifested in large budgets and claims to eminent domain, decision makers now tend to face greater constraints; those constraints make it difficult to address this increased uncertainty with traditional methods, such as relying on large safety factors. Third, a richer set of options for managing uncertainty ranging from adaptive design, to regional risk sharing, to the use of insurance and other financial instruments is increasingly available to planners. Analytical tools are needed to sort through the options and identify the most efficient portfolio of adaptations. Fourth, funders and users of infrastructure increasingly demand a higher level of service and resilience from their infrastructure and related systems.

DMU methods are increasingly incorporated into guidance documents worldwide.[13] These DMU guidelines for hydropower build on methods for risk assessment in infrastructure investments reviewed by the World Bank in a Policy Research Working Paper by Hallegatte et al. (2012), and for water resource managers, in particular, in the Decision Tree Framework (Ray and Brown, 2015). These methods continue to be developed, tested and applied to different contexts (Marchau et al., 2019), including in the hydropower sector. Here, the combination of reliance on local water resources with investment decisions regarding infrastructure projects that have a long life (both subject to increasing climatic variability under climate change) make the need for climate resilience planning critical. A summary of other DMU techniques is provided in the Decision Tree Framework document.

There are many types of DMU approaches and methods, most of which are related but emphasise different factors.[14] Most of these new DMU methods follow an "Agree-on-Decision" approach (Kalra et al., 2014), which starts by stress testing options under a wide range of plausible conditions, without requiring decision makers to agree on which conditions are more or less likely, and against a set of objectives or success metrics, without requiring decision makers to agree on how to aggregate or weight them. As a result, these methods are easier to apply in contexts with significant uncertainty or disagreement on values and objectives. By representing decisions as trade-offs and aiming for Pareto optimality, they promote constructive negotiation and consensus. By seeking designs of facilities and operating policies that are both flexible and robust, they balance risk aversion and opportunism. The highly risk averse decision maker would aim at robustness and likely over-build, whereas the opportunist decision maker would build to capitalise on the resources of the present moment and expect to be able to update the design in the future in response to change. DMU techniques allow the costs and benefits of each approach to be balanced. A growing set of case studies show that these methods can be applied in real-world contexts, give the same results as traditional methods when uncertainties are not large and do not need to be more costly or complicated than traditional approaches.

The European Financing Institutions Working Group on Adaptation to Climate Change (EUFIWACC) outlines processes that help integrate climate change resilience and adaptation into their investment activities. Their 2016 guidance note on emerging experience from practitioners describes high level good practice for taking into consideration the inherent uncertainties and complexities, aiming to develop flexible approaches that align with the climate risk profiles of projects and project partners as an approach to aid decision making under climate uncertainty. While this document is not hydropower specific, it includes a useful list of principles relevant to climate resilience and investment that may be relevant to the users of these guidelines.

Annex E

Example

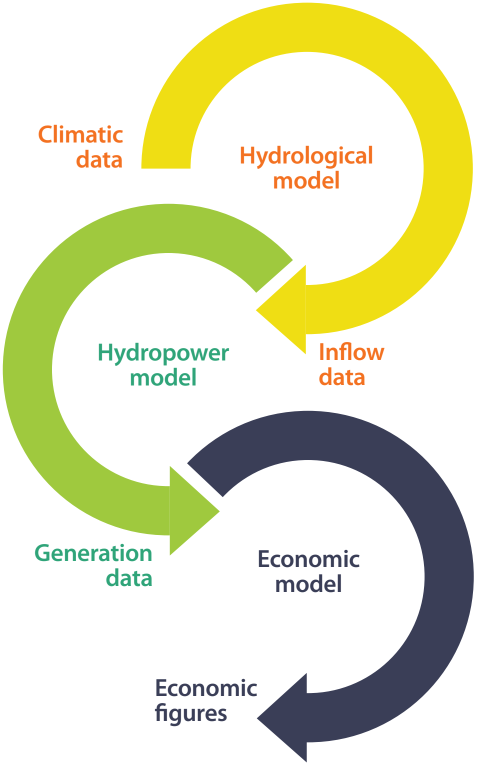
This example corresponds to Phase 3. Climate stress test and Phase 4. Climate Risks Management Plan. However, it only illustrates some of the steps in each phase. The example illustrates the climate stress test carried out under a comprehensive approach and shows how to carry out Step 4.3. Resilience analysis of the modified design options proposed in Step 4.2.

For the hydrological modelling, produce new sequences of weather variables to simulate climate change for a plausible range of future potential climate scenarios. This is done in two steps: (a) resample the historical record (e.g. using a weather generator) in order to develop a number (e.g. 10-30) of climate traces that are similar in overall statistics to the historical climate, but are representative of uncertainty in the future mean, variance, skew (extremes), and persistence (interannual autocorrelation), assuming climate stationarity; (b) apply climate shifts to the sample of natural variability traces.

Typically, climate shifts are applied to the variables that are represented by the most credible GCMs: long-term average basin-wide annual precipitation and temperature. The range of applied climate shifts is based on all changes that are considered possible, rather than simply probable. This range often extends beyond the typical range of an ensemble of climate model projections. The range can be sampled using a full-factorial sampling structure (matching every possible discrete change in temperature with one of the possible discrete changes in precipitation, regardless of the likelihood of the combination) or using more intelligent sampling techniques, such as Latin hypercube (McKay, 1979).

Run the hydrologic and water resources system model repeatedly for the entire period for many future climate scenarios for each of the water system plans under consideration (see Figure 5).

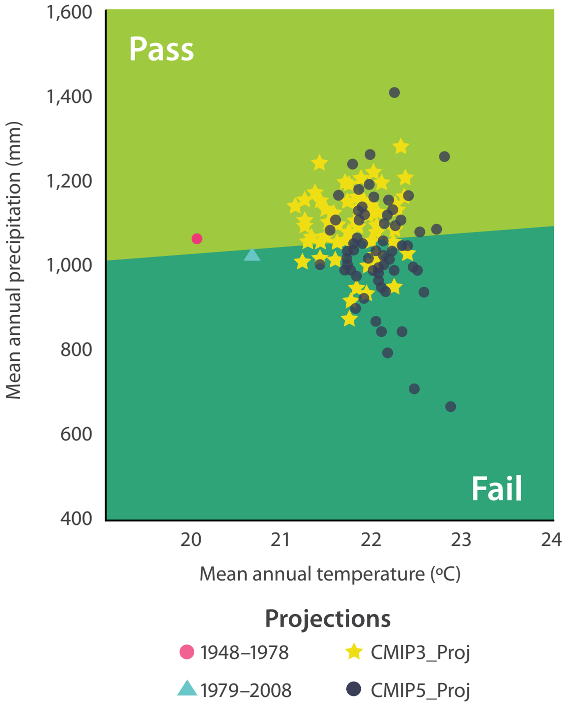
Figure 5. Representation of models that can be used in the stress test.



With the outcomes of the models (hydrological model coupled with hydropower model and then economic model), produce a climate response map (see Figure 6) showing the performance of the project across a wide range of possible climate states. This tool is used to identify climate states that result in unacceptable performance relative to a given levelised cost, EIRR or NPV threshold. The climate response map shows climate states that result in unacceptable performance relative to the threshold; the areas in red are deemed to be unacceptable and the green areas acceptable. Therefore, in this example, scenarios that are plotted in the red area or close to the threshold between the red and green would require further attention. Climate change fields from the climate model simulations may be used to inform the range of changes only, with questions of likelihood reserved for later stages of the stress test.

Identify areas in the climate response surface where performance of the system is in failure relative to the previously-defined performance thresholds. The failure scenarios, called vulnerability scenarios, are defined by the levels of combined precipitation and temperature (or other climate change variable, if applicable), above or below which the system fails to perform acceptably.

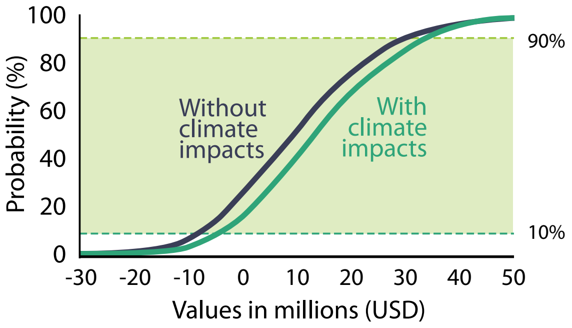
Figure 6. Example climate response map for a run-of-river hydropower project (Ray and Brown, 2015). Symbols refer to annual averages for temperature and precipitation for the periods shown. Downscaled general circulation model values are 20-year averages from 2030 to 2050.



A Monte Carlo analysis or other models will give a probability distribution curve of project risks with and without climate change. An illustrative example of an empirical cumulative distribution function is provided in Figure 7. These results are presented under a 'generic' distribution curve (assuming that each simulated run is equally likely and ranked in order of simulated project value) from a risk register analysis to show potential changes to project value related to project risks with and without climate change. Figure 7 shows only one climate change impacted scenario, but more mature graphs would present the impacts of as many climate change scenarios as needed, likely using ranges and uncertainty bounds.

From this distribution curve, for this particular design, a probabilistic assessment of the likely climate cost impacts on the existing project can be assessed.

Figure 7. Example distribution curve for incremental or decremental construction costs associated with project risks both with and without climate change impacts.



In Phase 4, after the selection of adaptation measures, similar distribution curves can be developed representing the altered vulnerability of the modified design project in Step 4.2.

In Step 4.3. the calculation of regrets (or loss) is fundamental to take a decision about the best modified design.

The regret of a design in any scenario is the difference or deviation between the performance of that design in that scenario and the performance of the best design for that scenario. Comparing 'regrets' can prove useful under conditions of uncertainty because it helps answer the following question: How bad might outcomes be if projections prove inaccurate? Comparing 'regrets' proves particularly useful when the likelihood of alternative scenarios is not known with any confidence.

To calculate regrets, first calculate the performance of each design in each scenario. Next, for each scenario identify the design that performs best in that scenario. Assign that best performing strategy zero regret for that scenario. Finally, assign every other strategy a regret in that scenario equal to the difference between its performance and that of the best performing strategy.

Note that regrets can be expressed in absolute or relative terms. Relative numbers may have a more relevant meaning to appraise deviation from the best performance target.

Tables 10 and 11 show a simple notional example of calculating regrets for two designs – A and B – and three scenarios – 1, 2 and 3. Assume the numbers represent net present economic value from electric generation from the project, which the owner/developers would like to be as large as possible.

Looking at Table 10, Design A performs best in scenarios 2 and 3, but worst in Scenario 1. Design A performs so poorly in Scenario 1 that is has a maximum regret of six compared to Design B's maximum regret of three (shown in Table 11). Thus, minimising the maximum regret criterion would select Design B.

If the owners/developers would be satisfied with a design that comes within three units of the best possible electric generation, Design B has satisfactory regret in all three scenarios, while Design A has satisfactory regret in two scenarios. Thus, the satisficing regret criterion would also suggest Design B as the most resilient. However, if owners/developers demanded a regret of two or less, the satisficing regret criterion would recommend neither design. In this case, the owners/developers might either seek an additional Design C with a regret of three or less in all three scenarios or revisit their requirement for a regret of three or less.

Table 10. Representation of net present economic value from electric generation performance.

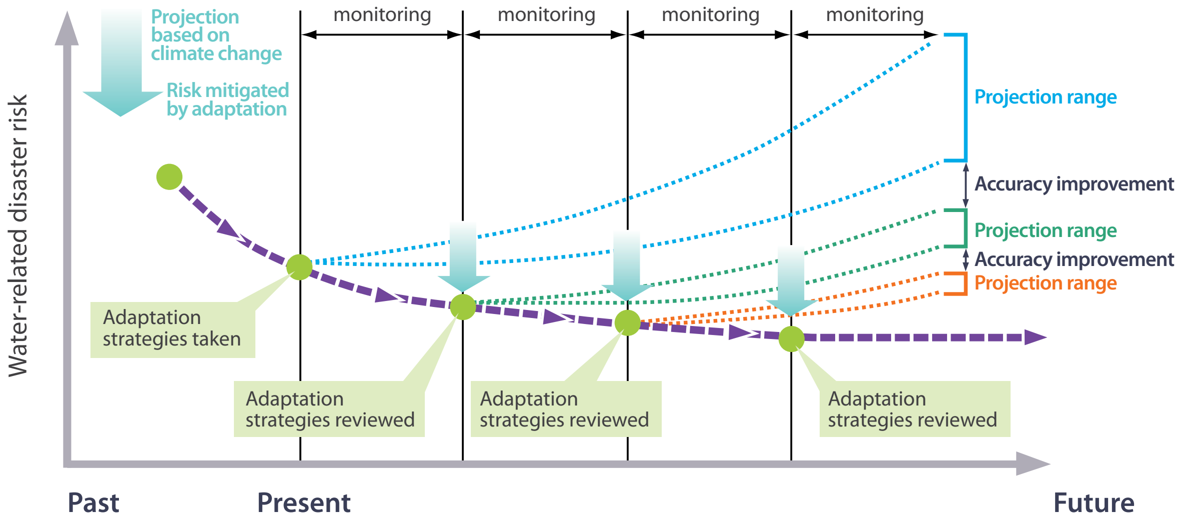
	Scenario 1	Scenario 2	Scenario 3
Design A	4	10	5
Design B	10	7	4

Table 11. Calculation of regrets between the options.

	Scenario 1	Scenario 2	Scenario 3
Design A	6	0	0
Design B	0	3	1

The adaptation pathway approach (as shown in Figure 8) can be also used to provide a list of low-regret/win-win resilience measures for consideration during the project.

Figure 8. No regrets approach to adaptive management (from ICOLD, 2016).



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