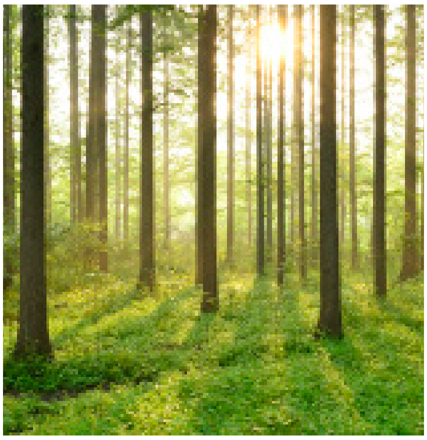
# IMPACT OF CLIMATE CHANGE ON DAM SAFETY

## RAPPORT 2023:947



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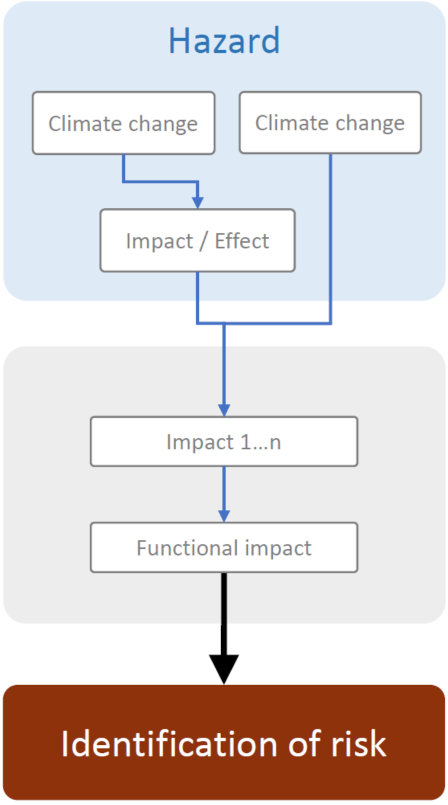

Energiforsk

# Impact of climate change on dam safety

## Literature review and initial analysis

**CLAES-OLOF BRANDESTEN**

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Translation of the Swedish Report 2022-908 May 2023.

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# Preface

**Knowledge about the climate and its changes is in strong development and the effects of a changing climate are relevant from a dam safety perspective, with discharge capacity and discharge safety in particular focus. In this project, current and relevant information has been compiled to lay a foundation for strategic climate adaptation work regarding dams.**

The project has been carried out by Brandesten Consulting with Claes-Olof Brandesten as project manager. The project's reference group has consisted of the Climate Committee - a committee for dam safety in a changing climate that has been appointed jointly by Affärsverket svenska kraftnät[1], Energiföretagen Sverige - Swedenergy[2], SveMin[3] and Swedish Meteorological and Hydrological Institute (Svenska kraftnät, Energiföretagen, SveMin och SMHI, 2021-05-06). The Climate Committee consists of:

- Maria Bartsch and Anna Engström Meyer (Svenska kraftnät),
- Hans Häggström and Sara Töyrä (SveMin),
- Peter Lindström, Agne Lärke, Björn Norell, Romanas Wolfsborg, Katarina Funning, Anders Frisk and Emma Wikner (Energiföretagen),
- Niclas Hjerdt and Jonas German (SMHI).

The project has been carried out within Energiforsk's program for Dam Safety with participation from the hydropower industry and Svenska kraftnät. The author is responsible for the content of the report.

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[1] Authority for the Swedish National Grid and the Central Dam Safety Authority.

[2] A non-profit industry and special interest organisation for companies that supply, distribute, sell, and store energy.

[3] The Swedish Association of Mines, Mineral and Metal Producers.

# Summary

**Society's greenhouse gas emissions have already affected the climate and further changes are expected. These changes will affect dam safety and require adaptation measures.**

This report presents the project "The impact of climate change on dam safety – A compilation of knowledge" whose purpose was to:

1. Compile and make available current knowledge about climate-related effects that is relevant from a dam safety point of view.
2. Form the basis for work regarding strategic climate adaptation work regarding dams and dam safety.

The report presents a literature review that includes methodology for analysis of and adaptation to climate change, as well as the identification of changes that may affect dam safety.

Using the results of the literature review, an analysis of climate change is carried out, which may lead to risks to dam safety. The analysis is based on the four driving climate parameters temperature, precipitation, wind with their combinations, and sea level. These will generally increase with the exception of wind where the picture is so far unclear. About seventy impact chains are reported that are used to identify risks that can affect dam safety.

The results do not show any new risks, but primarily they are already known risks that may be exacerbated by climate change that is relevant to dam safety.

Authorities and industry associations are advised to continue to monitor climate change and to make it easier for dam owners by taking the climate issue into account in their guides and guidelines.

# Keywords

Dam safety – Climate change – Climate indicator – Impact chain – Risk analysis.

# Sammanfattning

**Samhällets utsläpp av växthusgaser har redan påverkat klimatet och ytterligare förändringar är att vänta. Dessa förändringar kommer att påverka dammsäkerheten och ställa krav på anpassningsåtgärder.**

I denna rapport redovisas projektet ”Klimatförändringars påverkan på dammsäkerheten – En kunskapssammanställning” vars syfte var att:

- Sammanställa och tillgängliggöra aktuell kunskap om klimatrelaterade effekter som är relevant ur dammsäkerhetssynpunkt.
- Utgöra underlag för arbete vad avser strategiskt klimatanpassningsarbete rörande dammar och dammsäkerhet.

I rapporten redovisas en litteraturgenomgång som omfattar metodik för analys av och anpassning till klimatförändringar, samt identifiering av sådana förändringar som kan påverka dammsäkerheten.

Med användning av resultaten från litteraturgenomgången genomförs en analys av klimatförändringar som kan leda till risker för dammsäkerheten. Analysen utgår från de fyra drivande klimatparametrarna temperatur, nederbörd, vind med deras kombinationer, samt havsnivå. Dessa kommer generellt att öka med undantag för vind där bilden ännu så länge är oklar. Ett sjuttital effektkedjor redovisas som används för att identifiera risker som kan påverka dammsäkerheten.

Resultaten visar inte på några nya risker utan i första hand är det redan kända risker som kan komma att förvärras av klimatförändringar som är aktuella för dammsäkerheten.

Myndigheter och branschorganisationer rekommenderas att fortsatt följa klimatförändringarna och att underlätta för dammägarna genom att beakta klimatfrågan i sina vägledningar och riktlinjer.

# Nyckelord

Dammsäkerhet – Klimatförändring – Klimatindikator – Effektkedja – Riskanalys.

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# 1 Introduction

**Society's emissions of greenhouse gases have already affected the climate and further changes are expected. These changes will occur in the technical lifetime of dam facilities, which has already and will increasingly require adaptation measures.**

Changes in operating patterns and external factors due to climate change or the development of the energy system may result in changes in safety margins. Effects of a changing climate are therefore relevant from a dam safety perspective, with discharge capacity and discharge safety in particular focus. The number of dam facilities that can be affected is large and the time perspective for adaptation measures relatively long. In order to map risks and vulnerabilities and meet needs on a regional or national scale, the climate issue needs to be addressed continuously and in a structured manner.

With such starting points, the "Committee for Dam Safety in a Changing Climate" was formed, still called the Climate Committee, jointly by Svenska kraftnät, Swedenergy, SveMin (the principals for the guidelines for design flood determination for dams) and SMHI. The Climate Committee aims to evaluate the importance of the climate issue for dam safety and strengthen the development in terms of discharge safety and climate adaptation of dam facilities. The Committee has initiated several different activities with this purpose, of which the project that forms the basis of this report was one. The Climate Committee has also served as a reference group for the project.

The report is an account of the development project "Climate change's impact on dam safety – A knowledge compilation" whose purpose was to:

- Compile and make available current knowledge about climate-related effects that is relevant from a dam safety point of view.
- Form the basis for the Climate Committee's work with regard to strategic climate adaptation work regarding dams and dam safety.

The initial literature review covered methodology for climate change analysis and adaptation, which is presented in section 3, and the identification of climate changes that may affect dam safety, as reported in section 4.

Results from section 3 was applied for the presentation of current knowledge in sections 4 and on the basis of the two sections, the project was expanded with an analysis of climate change that may affect dam safety, which is reported in section 5.

# 2 Implementation of the Project

The project has included literature review, workshop, reconciliations with the Climate Committee, analysis and report writing, which is described below.

## 2.1 LITERATURE REVIEW

The literature review comprised two parts:

- Methodology for climate change analysis and adaptation.
- Identification of climate changes that may affect dam safety.

Identification of reports and articles describing methodology was done through internet searches and review of reference lists to find additional reports. The work is presented in section 3.

Identification of reports and articles describing climate change that can affect dam safety was initially done through searches at Energiforsk, NVE and in databases for various journals. Additional reports were identified by going through reference lists. The work is presented in section 4.

Search was conducted on Energiforsk's website with the keyword "Dam Safety" and filtered on hydropower with the keyword "Climate". Results are reported in Table 1. Manual search was also conducted on NVE's[4] website supported by keyword "Climate". In addition, a search was initially carried out with the help of SMHI among journals that are not openly available.

After this beginning, searches were continued on the internet based on found references in the above results and what was found thereafter. The number of references found, etc. can be found in Table 1. Some 50 of these were finally referenced in the report.

**Table 1** **Completed literature search with approximate number of found references**

| Source | Keywords | Number of References |
|---|---|---|
| Energiforsk | Dammsäkerhet (Dam Safety) | 230 |
| Energiforsk | Klimat / Vattenkraft (Climate / Hydropower) | 28 |
| NVE | Klima etc. (Climate etc.) (2015-2022) | 20 |
| Journals* | Dam safety & climate change | 35 |
| Internet** | Climate change dam safety, etc. against countries and bodies. | ca. 50 |

* Selection of databases with journals using SMHI financed by Svenska kraftnät.
** Searches were made against Norway, Finland, Canada (CEA, CDA) and generally.

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[4] NVE – Norges Vassdrags- og Energidirektorat – www.nve.no.

## 2.2 WORKSHOP

A workshop was held on May 18 with about 15 people from the industry, several of whom are members of the Climate Committee. The workshop was conducted on the basis of the methodology proposed by CEA (CEA, 2020) for energy companies in Canada (see section 3.9). The discussions focused on the first four steps of the methodology and included the formulation of goals and commitment to climate adaptation, critical and vulnerable facilities, as well as potential climate impacts and risks to dam safety. The workshop was documented in a special report (Brandesten, 2022).

## 2.3 DISCUSSIONS WITH THE CLIMATE COMMITTEE

Reports and discussions with the Climate Committee, which constituted the project's reference group, were held on four occasions in addition to the workshop – 19 January, 28 April, 20 September, and 5 December. In addition, the work was reported for the Design Flood Conference[5] on November 17, when feedback was also received.

## 2.4 ANALYSIS

In the analysis phase of the project, the initial summaries in Excel sheets used during the workshop were revised to correspond to impact chains according to SS-EN ISO 14091 (SIS, 2021) and as further described by GIZ & EURAC (GIZ & EURAC, 2017). However, instead of conducting a full risk analysis, the focus was on identifying potential risks to dam safety according to the revision of the methodology and described in section 5.1.

## 2.5 REPORT WRITING

A review edition of the report was sent to the Climate Committee for comments at the end of November. The review comments and suggestions received were taken into account in the present report.

The report used the terminology suggested by SS-EN ISO 14090 (SIS, 2019a) and SS-EN ISO 14091 (SIS, 2021).

In May 2023, the report was translated into English and a second Swedish version with some corrections was published.

## 2.6 DISSEMINATION OF PROJECT RESULTS

As part of the dissemination of results, a webinar was held January 19, 2023. In addition, the work will be used as a basis for the Climate Committee's continued work. The report is published on Energiforsk's website.

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[5] The Design Flood Conference – a committee consisting of Svenska kraftnät, Swedenergy, SveMin – the principals of "Guidelines for determination of design floods for dams" – and SMHI, which follows up the guidelines application and takes initiatives to develop these when appropriate.

# 3 Literature Review of Methodology for Climate Change Analysis and Adaptation

A literature review of methodology for analysis of and adaptation to climate change was conducted in the project. The literature review identified several different initiatives to describe how analysis of and adaptation to climate change can be carried out. Initiatives have been taken both at national and international level as well as in various institutes and trade associations related to hydropower, mining and also especially dam safety.

The following presents a selection that has been judged to be of particular value for this development project. The report is mainly made in time order and therefore describes features of the development that has taken place.

## 3.1 SWEDISH DESIGN FLOOD GUIDELINES AND VARIOUS COMMITTEE WORK

For Sweden, common guidelines for determining design flows for dam facilities were issued 1990 (Flödeskommittén, 1990). These guidelines did not contain a direct reference to a changing climate, but a general statement that a revision of the guidelines may be necessary as a result of new meteorological and hydrological knowledge.

"The Committee for Supplementing the Design Flood Guidelines", KFR, was formed in 2002 on the initiative of Swedenergy, SveMin and Svenska Kraftnät. One of the Committee's tasks was to discuss a comprehensive approach on how to address the climate issue, although it was not yet considered realistic to establish guidelines in this regard. The results were presented in a report 2005 (KFR, 2005) and formed the basis for the revision of the guidelines in 2007.

In the second edition of the Swedish guidelines  ( (Svensk Energi, Svenska Kraftnät och SveMin, 2007), a developed methodology for calculating very extreme flows based on climate scenarios based on modelling and developed instructions for application in light of the uncertainties that a changing climate entail:

- The calculations should be reviewed regularly.
- Comparisons between occurring floods and calculated design floods should be carried out continuously.
- The sensitivity of the system to climate change should be analyzed using climate scenarios.
- New conditions may lead to the need to revise the design flood calculations.
- However, uncertainties about the future climate must not prevent the necessary dam safety enhancing measures from being taken.
- Moreover, due to those uncertainties, flexibility and margins should be created where appropriate.

"The Committee for Design Floods for Dam Facilities in a Climate Change Perspective" was formed in 2008 through an agreement between Svenska Kraftnät, Swedenergy, SveMin and SMHI. The committee's assignment was to lead a program to analyze and evaluate the importance of the climate issue for dam safety with regard to design flood determination and to initiate the necessary studies. The results were presented in a report 2011 (Kommittén för dimensionerande flöden för dammanläggningar i ett klimatförändringsperspektiv, 2011) and formed the basis for the revision of the guidelines in 2015.

The third edition of the Swedish guidelines (Svensk Energi, Svenska kraftnät och SveMin, 2015) was supplemented on the analysis of the system's sensitivity to climate change with the following:

- In this context, alternative climate scenarios describing high and less high assumptions about future greenhouse gas emissions should be used.
- Furthermore, at least three different global climate models should be used, for each of the different assumptions about future greenhouse gas emissions.
- For downscaling to the regional scale, a scientifically based and documented methodology should be used.
- Currently, dynamic downscaling is recommended.

In the period following the third edition, the IPCC made it increasingly clear that the climate is changing (IPCC, 2019) (IPCC, 2021). This was included in the fourth edition of the guidelines (Svenska kraftnät, Energiföretagen, SveMin, 2022) where it is stated that the climate is changing and that this should be considered when deciding on design floods. The guidelines further describe that a review of the calculation conditions should be carried out every ten years. Otherwise, the main elements of the guidance provided in the 2011 and 2015 editions are retained.

## 3.2 UK – GUIDANCE ON CLIMATE CHANGE – 2013

In the UK, a report was produced early on that includes both the potential impacts of climate change on reservoirs and dams, and guidance for a robust and auditable assessment of the risks of climate change and the impacts they may have (Atkins, 2013). The report summarizes some 30 potential climate changes that may have a direct or indirect impact on reservoirs and dams.

The methodology is based on a vulnerability assessment based on the form and function of the facilities, weather impact, current vulnerability, climate change leading to changes in exposure, and future vulnerability. Form refers to the overall technical design of the dam regarding dams and discharge devices. Function refers to the primary and main use of the facility, where hydropower, water supply, recreation, flow attenuation and environmental purposes are categories.

## 3.3 IPCC – CLIMATE RISK FRAMEWORK – 2014

IPCC – Intergovernmental Panel of Climate Change – is the UN's panel on climate change that compiles the current state of scientific knowledge about climate change, consequences, vulnerability and possible solutions.

Within the framework of its work, the IPCC describes methodology for analyzing climate risks to provide a basis for adaptation measures, which has been developed gradually. The current conceptual framework for this methodology changed 2014 (IPCC, 2014) by putting risk at the centre against previous vulnerability, as Figure 1 below shows.

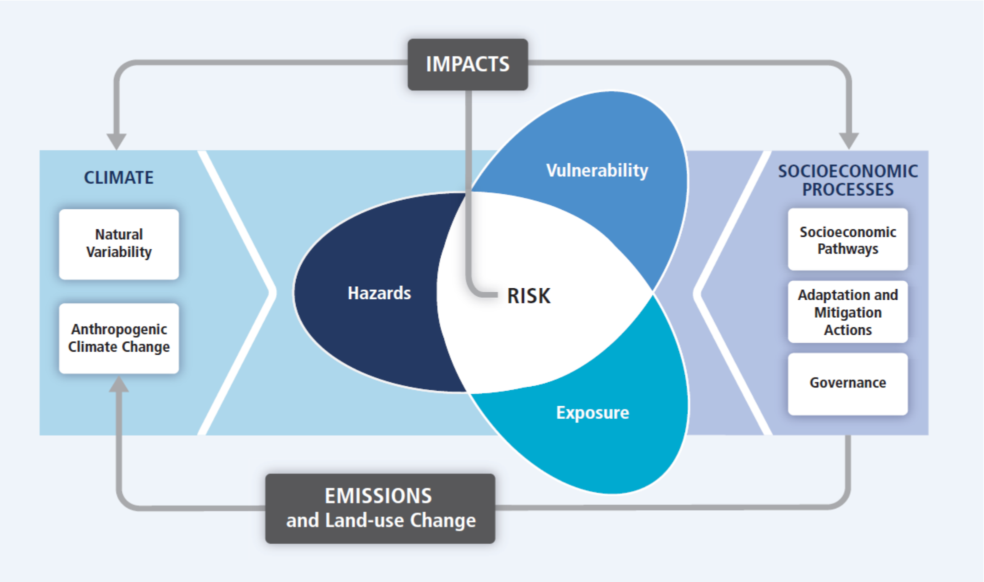

**Figure 1. IPCC AR5 risk-centred conceptual framework (IPCC, 2014).**

According to this approach, risk is a product of probability of hazards, exposure and vulnerability, which can be expressed as

Risk = *ƒ* (Probability of Hazards x Exposure x Vulnerability)

The probability refers to the hazards; or "the probability of hazardous events/trends occurring" while exposure and vulnerability are combined as the consequences, or "effects, if these [hazardous] events/trends occur".

## 3.4 ICOLD – BULLETIN 169 ON CLIMATE CHANGE – 2016

ICOLD Bulletin 169 on Global Climate Change, Dams, Reservoirs and Related Water Resources (ICOLD, 2016) aims to assess:

- The risk to dams and reservoirs as a result of climate change;
- The role of dams and reservoirs in adapting to climate change.

With regard to the nature of climate change, it is pointed out that, from a given baseline, it may include changes in mean values, changes in variability, or both of these in accordance with Figure 2.

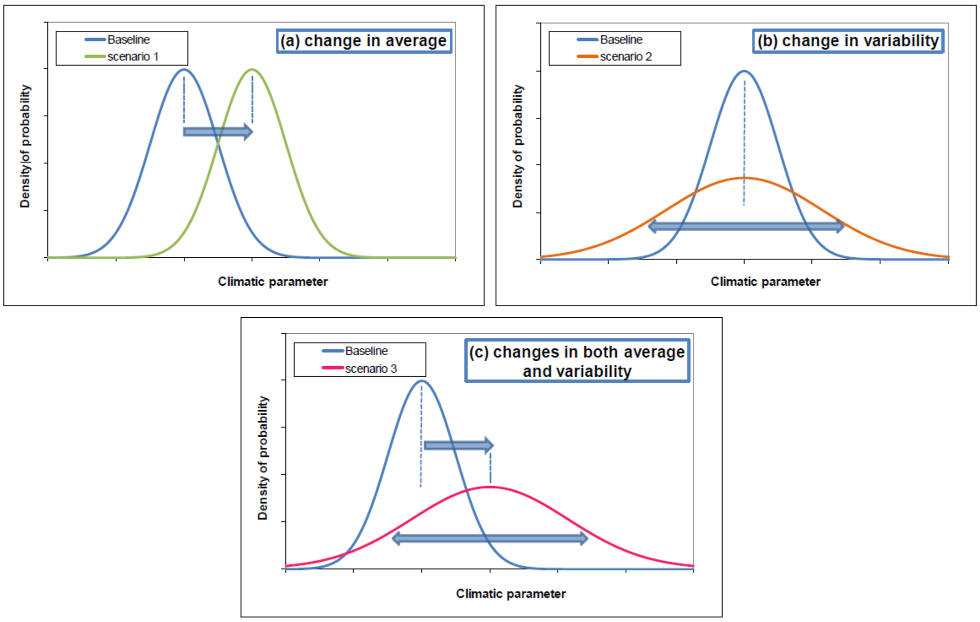

**Figure 2.** **Types of climatic parameters changes through schematic change of their density of probability: (a) shift of the average, (b) change in the variability, and (c) combination of both (ICOLD, 2016).**

It is also noted that climate change is only one of the drivers of change in the world's water resources. Socio-economic drivers will have as much, if not more, impact on water resources than climate change. The most important socio-economic driver is considered to be the growing world population.

The Bulletin concludes with three general recommendations:

- Adopt a whole-of-system approach to the system being analyzed.
- Apply an adaptive management process.
- Collaborate with a wide range of disciplines, interests and stakeholders.

### 3.5 GIZ & EURAC – GUIDE TO CLIMATE RISK ANALYSIS – 2017

The German aid organization GIZ, together with the private research institute EURAC, has developed guidelines on climate adaptation. In 2014, they published guidance for standardized vulnerability assessments (GIZ and EURAC, 2014) which was based on the conceptual framework of the IPCC at the time (see section 3.3). After the IPCC changed this, a supplement was made that assumes that risk is the central concept (GIZ & EURAC, 2017).

Based on the basic question "What contributes to the risk?", impact chains are developed according to a step-by-step methodology. Impact chain is seen as an analytical tool that helps to better understand, systematize and prioritize the factors that drive risks in a system.

The structure of an impact chain is shown in Figure 3, where the three parts hazard, exposure and vulnerability that contribute to risk are shown, together with the intended chain from climate signal/change with different stages of impact and impact.

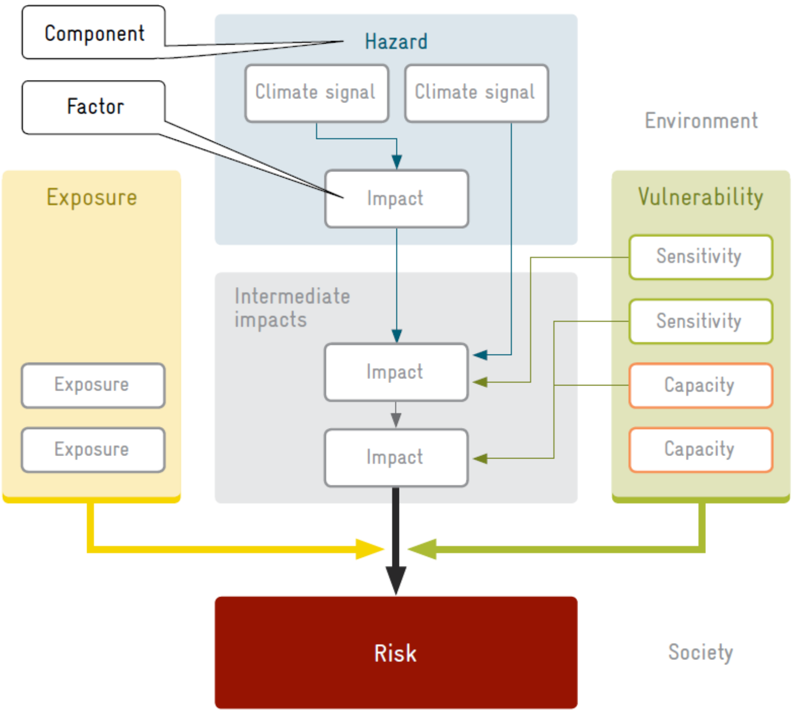

**Figure 3** **Structure of an impact chain according to the IPCC AR5 approach (GIZ & EURAC, 2017)**

According to GIZ & EURAC, the elements of an impact chain can be described as: A climate signal, for example a heavy rain, can lead to a direct physical impact, such as a flood, causing a sequence of intermediate impacts, which finally lead to the risk. Further details and examples are described in terms of application of the methodology.

## 3.6 SWEDEN'S NATIONAL STRATEGY FOR CLIMATE ADAPTION – 2018

In 2018, the Swedish Parliament adopted Sweden's national strategy for climate adaptation. The overall aim of the strategy is to strengthen long-term climate adaptation work in Sweden and the national coordination of climate adaptation. Four goals are formulated for the work on climate adaptation (Proposition 2017/18:163):

- The Government's goal for society's adaptation to a changing climate is to develop a long-term sustainable and robust society that actively responds to climate change by reducing vulnerabilities and seizing opportunities.
- The climate adaptation goals of the Paris Agreement and the 2030 Agenda with the global goals for sustainable development will also be achieved.
- Objectives should be taken into account in policies, strategies and planning at national level and integrated into ordinary activities and responsibilities.
- Further needs for targets or clarifications of the Government's climate change adaptation targets for different policy areas, sectors or identified vulnerabilities should be analyzed.

Through the strategy, a national expert council for climate adaptation has been appointed to follow up and evaluate climate adaptation work in Sweden. The strategy includes 10 principles for climate adaptation (Proposition 2017/18:163):

- Sustainable development – the interests of present and future generations are taken into account.
- Mutual support – between measures for climate adaptation and reduced climate impact.
- Scientific basis – measures must be based on a scientific basis incl. knowledge from the IPCC.
- Precautionary principle – potential detected risks are managed even if the available scientific knowledge is insufficient for a reliable conclusion.
- Mainstreaming of measures – where possible, all societal actors integrate measures into existing strategies and plans.
- Flexibility – measures are designed to be flexible and robust for different courses of action in the future.
- Management of uncertainty – measures are analyzed based on several possible outcomes of emission scenarios.
- Risk management – likely risks with serious consequences to be addressed.
- Time perspective – measures are adapted to take into account the service life of current facilities.
- Transparency – applied regarding uncertainties, choice of scenarios, risks and time perspectives.

## 3.7 SGI – CLIMATE PARAMETERS FOR DIMENSIONING OF GEOSTRUCTURES – 2018 – AND LANDSLIDE RISK MAPPING – 2022

As part of the Swedish Geotechnical Institute's (SGI) action plan for sustainable construction on land, a report was produced in 2018 describing the effects of various climate loads on natural soil and geo-structures (Lundström, Dehlbom, Löfroth, & Vesterberg, 2018).

The report shows the link between climate loads, soil conditions, geo-structures and climate change, as well as the need for new knowledge. Such information is important for authorities and industry to be able to set the requirements and carry out the work needed to climate-proof facilities and buildings. The report does not cover contaminated sites, hydropower and tailings dams.

Based on the general climate parameters precipitation in the form of rain and snow, temperature and wind, climate loads are identified that are applicable when dimensioning natural soil and geo-structures. Climate loads that are relevant to consider based on future climate change include the following:

- Water levels, water pressure, water flow, water velocity, wave forces, current pressure and ice pressure.
- Groundwater level, pore pressure and groundwater flow (also affects soil weight and pressure).
- Temperature including amount of cold, zero passthroughs and snow cover.
- Snow load including thickness of snow cover.
- Wind load.

The report makes a systematic review of which data is used as input data to dimensioning loads and how climate loads are applied in current norms and regulations.

In 2022, SGI published a landslide risk map for the river Ångermanälven in several different interim reports. In the first, the work is summarized, and maps are presented with a description of how the results can be used in the work on climate adaptation in municipalities and counties (SGI, 2022a). The second report describes methodology and analysis with a more detailed description of the investigation's methods, inventories, surveys, calculations and analyses (SGI, 2022b).

## 3.8 IHA – GUIDE FOR ADAPTION – 2019

To facilitate the development of hydropower infrastructure that can withstand the risks of varying climatic conditions, IHA in 2018, together with a range of partners, developed a guide with the objective of providing practical and systematic guidance for hydropower engineers, operators and project owners to develop climate resilient projects. (IHA 2019).

The guidance covers the following phases, which are also further divided:

- 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.

Annex A summarizes examples of effects on hydropower projects from different climate stressors. Annex C of the guidance presents examples of structural and functional adaptation measures for new and existing hydropower projects for different climate variables.

## 3.9 CEA – GUIDE FOR ADAPTION – 2020

The Canadian Electricity Association (CEA) notes that climate change affects organizations differently and therefore adaptation is required to mitigate threats and maximize opportunities. They have therefore produced a guide for their member companies on adaptation to climate change and extreme weather (CEA, 2020). The guide covers issues that affect the entire electricity industry regarding production, transmission and distribution. The guide provides a framework consisting of an 8-step process according to Figure 4.

The CEA suggests that organizations may choose to incorporate the risk management in existing enterprise risk processes, in asset management programs, or in other risk-based management systems such as ISO 14001 on environmental management (CEA, 2020).

The guide includes a number of appendices with lists of different assets and activities, potential climate impact, adaptation measures, etc. In its appendix 3, CEA presents a list of potential climate impacts that may be relevant for its member companies. The list and the parts concerning electricity production with hydropower and dam safety is presented in Attachment B:.

**Figure 4** **CEA's methodology for climate change adaption (CEA, 2020)**

## 3.10 SIS – STANDARDS FOR ADAPTION TO CLIMATE CHANGE – 2019 & 2021

Swedish Institute for Standards (SIS) has through its Committee on Environmental Management (SIS/TK 207) translated standards for governance of work on adaptation to climate change, with SS-EN ISO 14090 on Principles, requirements and guidelines (SIS, 2019a) and SS-EN ISO 14091 on vulnerability, impact and risk assessment guidelines (SIS, 2021). Access to these standards for reading on screens is provided by a special agreement between SIS and the Swedish Meteorological and Hydrological Institute for 2022.

EN ISO 14090 has as its main objective to provide organizations with a consistent, structured and pragmatic approach to prevent or minimize the damage that climate change could cause and exploit the opportunities. The methodology enables organizations to adequately consider climate change adaptation when developing, implementing, improving and updating their policies, strategies, plans and operations.

EN ISO 14091 contains guidelines on different methods for assessing the risks associated with climate change. SS-ISO 31000 on risk management (SIS, 2018) is promoted as an excellent complement as it can help organizations manage the risks identified and assessed in EN ISO 14091.

Both EN ISO 14090 and 14091 contain terms and definitions that have guided the work. Several of these are reported in Attachment A:.

SS-EN ISO 14091 refers to GIZ and EURAC (GIZ & EURAC, 2017), see section 3.5.

### 3.11 ICMM – 2020 & 2021

The International Council on Mining and Metals (ICMM) describes itself on its website as "a leadership organization working for a safe, fair and sustainable world enabled by responsibly produced minerals and metals" (ICMM, 2022). ICMM brings together a third of the global metals and mining industry, along with key partners. For Sweden, it can be noted that Boliden Mineral AB is a member of ICMM.

In its position statement on climate change, ICMM has made ten statements for its members to acknowledge for their activities (ICMM, 2021):

1. The need for an urgent global response to the threat of climate change, across all areas of society and the economy.
2. The need to support the goals of the Paris Agreement to limit the increase in the global average temperature to 2°C and pursue efforts to limit the increase to 1.5°C.
3. The critical role that the mining and metals sector plays in supporting the global transition to a low carbon economy by continuing to contribute to the sustainable production of commodities essential to the energy and mobility transition, working with our partners and key suppliers along our value chains.
4. The need to reduce emissions from the extraction and use of mining products and support collaborative market-based approaches to accelerate the use of low-emission technologies as part of a transition to a low carbon energy mix. At the same time, we also recognise the practical challenges that some less developed countries with domestic supplies of fossil fuels will face in making that transition.
5. That climate and energy policy should be technology neutral and rely on market-based approaches to enable least cost abatement solutions.
6. The vital role that a broad-based, predictable, long term carbon price can play, alongside other market mechanisms to drive reduction of greenhouse gas emissions and incentivise innovation.
7. The importance of providing climate-related disclosure in order for all stakeholders to measure and respond to climate change risks and opportunities.
8. The role of nature-based solutions in climate mitigation and adaptation.
9. The prioritisation of emission reduction initiatives and technologies, recognising the role for carbon offsets for hard-to-abate emissions.
10. The role of a circular economy in reducing emissions associated with the extraction and use of mining products by increasing resource efficiency in production and promoting the re-use and recycling.

ICMM is one of three initiators of the Global Industry Standard on Tailings Management (GISTM) published in 2020 (Global Tailings Review, 2020).

The issue of climate change is incorporated into six of the requirements for the management of tailings. These requirements are 2.1 and 2.2 – on interdisciplinary knowledge base, 3.1 – on resilience to climate change, 3.3 – on climate change considerations in the planning of new facilities, 3.4 – on climate change considerations in the management of facilities and 5.3 – on water balance model.

GISTM has been supplemented with a guide, adapted to the standard, focusing mainly on technical issues and recommending good practices for design, construction, operation and closure (ICMM, 2021b) and with conformance protocols to assess compliance with the standard (ICMM, 2021a).

The conformance protocol contains references to various standards to support a compliance assessment, in particular the ISO standard from 2019 ( (SIS, 2019a)), ICMM's position statement on climate change (ICMM, 2021), and a climate change understanding tool available to ICMM members (Mining Climate Assessment Tool - MICA).

## 3.12 SMHI – CLIMATE INDICATORS & CLIMATE SCENARIO SERVICE – 2022

Based on available climate information for Sweden, SMHI has developed 11 climate indicators to continuously monitor the development of the climate over time (Kjellström, o.a., 2022). The indicators are described in terms of the geographical areas they cover, the starting year of the time series, etc. They are:

- Temperature (annual and seasonal averages for the country)
- Precipitation (annual and seasonal averages for the country)
- Extreme precipitation (average and number of cases for the country and annual high at station level)
- Sea level (average for 14 stations)
- Sea ice (maximum extent of the Baltic Sea and Kattegat)
- Number of days with snow cover (for country and parts of the country)
- Winter's greatest snow depth (for country and parts of the country)
- Spring flood start (average for the north of the country)
- Length of the growing season (south and north of the country)
- Global radiation (annual and seasonal averages for the country)
- Geostrophic wind (average, maximum value, number of days, wind energy for 9 triangles across the country).

SMHI has also developed an in-depth climate scenario service (SMHI, 2022a) within which meteorological, hydrological, and oceanographic climate indicators can be selected to provide a basis for future changes. Changes are reported for whole years, seasons or months, both for different emission scenarios and for different periods. For the meteorological climate indicators can be selected if absolute or deviation values are presented. For the hydrological climate indicators, calculations have been made for 40 000 sub-basins in the country, which are reported per tributary basin.

SMHI also reports future mean sea levels for Sweden's coastal municipalities (SMHI, 2022b).

# 4 Identification of Climate Changes that May Affect Dam Safety

A literature review was conducted to identify climate changes that may affect dam safety. The approach was broad to cover changes that can affect different aspects of dam safety. Sometimes the identified climate change describes an entire cause-and-effect chain right up to the impact on dam safety and sometimes not.

A systematic review and description of which changes have already occurred, or which can be expected to occur was not carried out within the framework of the project, but some information on this has been included.

The identification can be equated to what is referred to in EN ISO14091 (SIS, 2021) as screening, but has been reported at a qualitative and overall level and not for any facility or activity.

The report was structured based on climate parameters according to SS-EN ISO 14090 (SIS, 2019a) which were revised for the purpose of the study in accordance with Table 2.

**Table 2 Selection and classification of climatic parameters**

| Climate parameters according to SS-EN ISO 14090 (SIS, 2019a) | Climate parameters in this study |
|---|---|
| • Temperature | • Temperature (T) |
| • Precipitation | • Precipitation (P) |
| • Wind speed and direction | • Wind (W) |
| • Rising sea levels | • Sea level (S) |
| • Freeze-thaw cycles<br>• Humidity | • Combinations of T, P, W and S with thunder, snow and ice (C) |

As can be seen from the table, the climate parameters temperature, precipitation, wind and sea level were selected in accordance with EN ISO 14090. In this study, a special climate parameter was introduced to describe different combinations of temperature, precipitation, wind and sea level, which also includes thunderstorms, snow and ice. Snow, for example, requires a combination of both precipitation and a low temperature to fall out. The parameters of freeze-thaw cycles and humidity mentioned by EN ISO 14090 were attributed to combinations of these climate parameters. River flow, which are central to hydropower and dam safety, can also be considered to belong to combinations of climate parameters.

Effects of changes in the different climate parameters are presented in tables with references where relevant. Reference is often made to the UK (Atkins, 2013), IHA (IHA, 2019) and CEA (CEA, 2020) containing checklists, but also to specific reports where the effect has been described in more detail.

For the different climate parameters, groups of possible climate indicators are also presented in tables with reference to SMHI's in-depth climate scenario service (SMHI, 2022a), see section 3.12, with several sources.

## 4.1 A FEW INTRODUCTORY WORDS ON CLIMATE AND CLIMATE CHANGE

By climate is meant the long-term characteristics of the weather observed over time. Climate includes temperature, precipitation and wind, but also air pressure, humidity and atmospheric particles.

The climate is affected by radiation from the sun, circulation in the atmosphere and in the sea, and topography on land and in the sea. Human activity also affects the climate through the release and release of greenhouse gases that lead to increased temperature in the atmosphere.

The climate drives several different processes, where those with the strongest connection to hydropower are the hydrological ones. Hydrological processes include precipitation, evaporation, runoff, storage, condensation, freezing and melting. Other processes that climate affects are weathering, corrosion, photosynthesis and other biological processes.

Sweden's climate is characterized by high variability on time scales from single days, via months and years, to several decades. According to all climate scenarios, we will have this kind of variability in the future as well. For Sweden, this is particularly due to continued shifting of the seasons, gradually higher temperatures and generally more precipitation, which to a lesser extent falls as snow. It is also about changes in extremes, with more intense heat waves and less frequent cold snaps that will not be as cold as before. The scenarios also point to more intense precipitation but also some increased risk of drought during rainfall poor years. (Kjellström, Strandberg, & Lin, 2021).

An elucidation of aspects of climate change from a dam safety perspective is given in an Energiforsk report (Holst & Thanke Wiberg, 2019).

## 4.2 TEMPERATURE – T

Climate change with respect to increasing temperature includes both changes in permanent and temporary conditions, which can have both direct and indirect impacts on dam safety. Changes in temperature regarding higher mean, increased variation and worse extremes with potential effects of these are reported in Table 3.

As can be seen from the table, it is primarily temperature changes in the form of increased variations and higher extremes that can have a direct impact on dam safety. In most cases, temperature changes have effects that can indirectly lead to an impact on dam safety. Descriptions of such causal relationships are given in Section 5, where so-called impact chains are presented.

The temperature in Sweden is increasing and will increase in the future. The increase is expected to be greater in the northern parts of the country than in the south. (Kjellström, o.a., 2022).

**Table 3** **Temperature changes – potential direct and indirect effects**

| Temperature change | Effect | Reference |
|---|---|---|
| Increase | Warmer water in lakes and streams | UK, IHA, CEA |
| | Longer growing season | UK, CEA |
| | Later icing & less ice thickness | See section 4.5 |
| | Reduced snow cover & earlier snow melt | See section 4.5 |
| | Reduced frost depth & shorter frost period | IHA, a) |
| | Glacier melting | b), c) |
| | Increased energy demand | UK, CEA |
| Increase – variation – extremes | Impact electrical components | IHA, CEA |
| | Thermal expansion concrete structures | IHA, d) |
| | Thermal expansion mechanical structures | |
| | More difficult working conditions | UK, CEA |
| | More zero passthroughs with more freeze/thaw cycles | CEA |
| | Swelling ice caps | |
| | Extreme snowmelt & more melting periods | |
| | Increased power need | UK |
| | Freezing in pipes and pumping systems | e) |

Not: UK = (Atkins, 2013), IHA = (IHA, 2019), CEA = (CEA, 2020)

a) Frost and thawing can affect the stability of tailings dams (Reynier, 2018)

b) A study of all Swedish glaciers – 294 – has shown that since about 1916 to 2008, the volume of these has decreased by 41% from 19.4 to 11.5 km$^3$. If the accelerated rate of decline since 2002 continues, most glaciers will disappear by 2070 (Hamré, 2015).

c) A study of Norwegian glaciers shows that their area has decreased by 15% between 1999-2006 and until 2018-2019 (Andreassen, 2022).

d) A Spanish study of the influence of increasing temperatures on concrete structures states that thermal loads are the most significant factor for cracking in vault dams (Santillán, E. Salete, & Toledo, 2015).

e) Experience from the operation of a tailings reservoir shows that low temperatures together with optimized water management that leads to small volumes in the system increase the risk of freezing and operational problems (Töyrä, Lundell, & Bjelkevik, 2017).

Table 4 presents groups of potential climate indicators. Most of these are reported by SMHI (SMHI, 2022a) compare section 3.12. But the table also contains climate indicators that are not covered by SMHI's in-depth climate scenario service.

**Table 4** **Potential climate indicators regarding temperature**

| No | Climate indicator | Source |
|---|---|---|
| T-1 | Average, minimum, and maximum values for years, seasons and months | SMHI |
| T-2 | Diurnal and seasonal amplitudes | SMHI |
| T-3 | Number of days with frost, cold, zero passthroughs, high summer heat and tropical heat | SMHI |
| T-4 | Longest heat wave in days | SMHI |
| T-5 | Beginning, *end* and duration of the growing season | SMHI |
| T-6 | Year-on-year cooling and heating degree days | SMHI |
| T-7 | *Evaporation* and effective precipitation | SMHI |
| T-8 | If precipitation falls as rain or snow | |
| T-9 | *Extent, duration, strength* and water content of snow cover | FLK, SMHI |
| T-10 | The start of the spring flood | FLK |
| T-11 | Length and depth of the frost period | |
| T-12 | Start of icing, ice thickness and duration of ice cover | |
| T-13 | Water temperature in lakes and streams | |

Note: SMHI = (SMHI, 2022a), FLK = Design Flood Conference. *Italics* – indicator that is not reported by SMHI.

## 4.3 PRECIPITATION – P

Climate change in precipitation includes both changes in permanent and temporary conditions, which can have both direct and indirect impacts on dam safety. Changes in precipitation related to higher meanness, increased variability and worse extremes with potential effects of these are reported in Table 5.

Precipitation is expected to increase in the future, although the signal is not as clear as for temperature. The initial increase is smaller in the southern parts of the country and then probably heading for a decrease. (Kjellström, o.a., 2022).

A larger part of the precipitation is expected to fall as rain and a smaller proportion as snow (Kjellström, Strandberg, & Lin, 2021).

**Table 5** **Increased precipitation, increased variability, and worse extremes with potential effect**

| Precipitation change | Effect | Reference |
|---|---|---|
| Increase | Saturated soil and *fill material in embankments* | UK, IHA |
| | Increased flows in watercourses | UK, |
| Increase – variation – extremes | More frequent and heavier downpours | UK, IHA, CEA, f) |
| | Increased extreme flows | UK, IHA |
| | Flooding along watercourses | |
| | Flooding locally, in tunnels and in power stations | IHA |
| | Damage to roads, dams and electrical equipment | IHA |
| | Erosion and landslides along shores and on land | IHA, g) |
| | Increased amount of debris and sediment | IHA |
| | Impaired accessibility | |

Note: UK = (Atkins, 2013), IHA = (IHA, 2019). *Italics* – not specifically mentioned by the UK or IHA.

f) During the period 1996-2017, there are no clear temporal trends regarding the size and frequency of heavy rainfall in Sweden, but these are generally at a constant level. Extreme daily precipitation since 1900 also shows no clear trends at regional level. At the national level, a slight increase is indicated in both the country's highest annual rainfall since 1881 and the presence of large, widespread 2-day rainfall since 1961. (Olsson, o.a., 2017).

g) SGI has begun to publish data for the assessment of landslide risks along watercourses in current and future climates (SGI, 2022a) which can serve as a basis for assessing risks that could affect dam safety.

In Table 6 groups of potential climate indicators are presented. Several of these are reported by SMHI (SMHI, 2022a), compare section 3.12. But the table also contains climate indicators that are not reported by SMHI.

**Table 6** **Potential climate indicators related to precipitation.**

| No | Climate indicator | Source |
|---|---|---|
| P-1 | Average, min, and maximum values for years, seasons, months, *14 days, week* | SMHI |
| P-2 | Number of days without, with heavy and extreme precipitation | SMHI |
| P-3 | Frequency 1, 2, 4, 6, 12, 24, 48 hours of precipitation | |
| P-4 | Frequency of Haldo-rains[6] | FLK |
| P-5 | Longest dry spell in days | SMHI |

Note: SMHI = (SMHI, 2022a), FLK = Design Flood Conference. *Italics* – Indicator not disclosed av SMHI.

## 4.4 WIND – W

Climate change related to wind can include both changes in permanent and temporary conditions, which can have both direct and indirect impacts on dam safety. Changes in wind regarding wind direction, increased variation and worse extremes with potential effects of these are reported in Table 7.

Changes in the future wind climate, as a rule, are small and different models give different results (Kjellström, Strandberg, & Lin, 2021).

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[6] Haldo Vedin was a meteorologist at SMHI who has given his name to Haldo-rains, which is precipitation events that amounts to at least 120 mm in 24 hours.

**Table 7** **Increased wind, increased variation, and worse extremes with potential effects.**

| Wind changes | Effect | Reference |
|---|---|---|
| Change of wind direction | Damage to slopes, reservoirs and dams | |
| | Impact evaporation | IHA |
| Increase – variation – extremes | Damage to dam erosion protection | |
| | Set-up of reservoirs and wave formation | CEA |
| | Damage to buildings, masts and poles | CEA |
| | Windfalls | |
| | Snow reef | |

Not: IHA = (IHA, 2019), CEA = (CEA, 2020)

In Table 8 groups of potential climate indicators are presented. SMHI's in-depth climate scenario service does not contain a climate indicator regarding wind (SMHI, 2022a). No other sources have been identified either.

**Table 8** **Potential climate indicators related to wind**

| No | Climate indicator | Source |
|---|---|---|
| W-1 | Average, minimum and maximum values for years, seasons and months 10 m level | |
| W-2 | Storm and hurricane frequency | |
| W-3 | Prevailing wind direction | |

## 4.5 COMBINATIONS OF T, P, AND W WITH THUNDER, SNOW, AND ICE

Climate change with respect to combinations of temperature, precipitation, wind, and sea level includes thunderstorms, snow, ice, and more. These may include both changes in permanent and temporary conditions, which may have both direct and indirect impacts on dam safety.

Changes in combinations of different climate parameters with potential effects of these are reported in Table 9.

**Table 9** **Combinations of different climate parameters with potential effects**

| Combinations of T, P & W | Effect | Reference |
|---|---|---|
| Increased humidity | Increased degradation, corrosion and rotting | IHA, CEA |
| Longer dry spells and heat waves | More forest fires | CEA, h) |
| Increased evaporation | Lower river flows | |
| Thunderstorms with lightning more often | More forest fires and damage to equipment | UK, IHA, CEA |
| Freezing rain / ice storms more often | Icing on equipment, wires | |
| Increased snow loads | Snow load on buildings, wires, forests | UK |
| Increased ice loads | Freezing, ice fouling, swelling ice cover | i), j), k) |
| Reduced snow cover | | l) |
| Reduced ice cover | | m) |

Note: UK = (Atkins, 2013), IHA = (IHA, 2019), CEA = (CEA, 2020)

h) Experiences of the forest fire in 2018 in river Ljusnan point to a number of factors that can affect dam safety; Access to the dam facilities is made more difficult, the electricity supply is cut off, backup power units are after a while dependent on the supply of fuel along the road network, electronic communications for monitoring, remote operation are disrupted and voice communication for coordinating measures at the plants is made more difficult (Jenvald & Morin, 2019).

i) Some of the dam safety aspects to consider are ice load, freezing against the ice cover in the reservoir, freezing against nearby concrete structures, ice swelling / ice growth downstream of the spillway hatch, kravis and low temperatures that affect electrical, mechanical and hydraulic systems (Bennerstedt, Åberg, & Halvarsson, 2021).

j) Ice loads against dams can be divided into ice loads due to thermal expansion and ice loads due to short-term regulation. Ice loads due to thermal expansion may be affected by a changing climate with faster temperature variations and more and faster 0 passes (Holst & Thanke Wiberg, 2019).

k) In a Norwegian study of three hydropower reservoirs, it is shown that the duration of ice cover will be greatly reduced (Gebre, Boissy, & Alfredsen, 2013).

l) A Norwegian study found that the extent of snow cover decreased between 1961 and 2010, especially at the end of the snow season, with a corresponding decrease in snow water content except at high altitudes. A comparison between the periods 1961-1990 and 1981-2010 showed that the extent of the snow cover decreased by more than 20,000 km2, mainly north of 63°C. (Rizzi, Brox, Howard, Gisnås, & Tallaksen, 2018).

m) A Finnish study of a couple of areas indicates that the availability of snow in Finland has decreased significantly over the past 100 years due to climate variations and climate change (Irannezhad, Ronkanen, & Kløve, 2015).

Table 10 groups of potential climate indicators are presented. Those stated are reported by SMHI (SMHI, 2022a), compare section 3.12.

**Table 10** **Potential climate indicators regarding combinations of temperature, precipitation, and wind**

| No | Climate indicator | Source |
|---|---|---|
| C-1 | Average, minimum, and maximum values for years, seasons and months (cf. T-1) | SMHI |
| C-2 | Average, minimum, and maximum values for years, seasons and months (cf. N-1) | SMHI |
| C-3 | Number of days without precipitation (cf. N-2) | SMHI |
| C-4 | Maximum dry period in days (cf. N-5) | SMHI |
| C-5 | Longest heat wave in days | SMHI |
| C-6 | Effective rainfall, average | SMHI |
| C-7 | Soil moisture, average | SMHI |

Note: SMHI = (SMHI, 2022a)

## 4.6 RIVER FLOWS

For river flows, a separate report is made in this section, although flows can be seen as the result of a combination of different climate parameters.

Climate change related to river flows can include both changes in permanent and temporary conditions, which can have a direct impact on dam safety. Changes in flows with potential effects of these are reported in Table 11.

**Table 11** Changes in river flows with potential effects

| Flow changes | Effect | Reference |
|---|---|---|
| Increase | Ökad magasinsfyllnad | IHA, n) |
| Increase – variation – extremes | Changing seasonal patterns | UK, CEA, o) |
| | Increased need for high spills | IHA, p) |
| | Increased need for winter spillage | q) |
| | Increased erosion along watercourses | IHA, CEA |
| | Increased of debris | IHA, CEA |

Not: UK = (Atkins, 2013), IHA = (IHA, 2019), CEA = (CEA, 2020)

n) In the future, an increase in water availability is expected throughout the year in northern Sweden. In southeastern Sweden, instead, a decrease is expected, which is due to increased evaporation. In other parts, the change in water availability during a year is more difficult to assess. (SMHI, 2022c)

o) In the future, increased temperatures will bring forward the spring flood in the northern and central parts of the country (Arheimer & Lindström, 2015).

p) For Sweden, no trend can be discerned in terms of year-high flows over the past 100 years (Arheimer & Lindström, 2015).

q) Increased need for spill in winter is mentioned as a possible change in operating patterns as a result of climate change, which can lead to difficulties both in opening frozen gates and in closing open gates (Holst & Thanke Wiberg, 2019).

Table 12 groups of potential climate indicators are presented. Several of those stated are reported by SMHI (SMHI, 2022a), compare section 3.12. But the table also contains climate indicators that are not covered by SMHI's in-depth climate scenario service.

**Table 12** **Potential climate indicators of river flow**

| No | Climate indicator | Source |
|---|---|---|
| F-1 | Average, *minimum and maximum values for years, seasons, months, 14 days, week* | SMHI |
| F-2 | Frequency 1, *2, 4, 7, 14, 30* days of discharge - 50 - *10 000 recurrence interval* | SMHI |
| F-3 | High water events today and in the future | FLK |
| F-4 | Snow water content – measured, calculated – average and annual high | FLK |
| F-5 | Percentage of filling of reservoirs | FLK |
| F-6 | More downpours and extreme rainfall volumes (cf. N-1 & N-3) | SMHI |
| F-7 | Frequency Haldo-rain (cf. N-4) | FLK |

Note: SMHI = (SMHI, 2022a), FLK = Design Flood Conference. *Italics* – indicator not reported by SMHI.

## 4.7 SEA LEVEL

Sea-level climate change can include both changes in permanent and temporary conditions, which can have both direct and indirect impacts on dam safety. Changes in sea level with potential effects of these are reported in Table 13.

In the context of global warming, sea levels are rising as a result of thermal expansion and increasing melting of land ice and glaciers. According to the IPCC, the average sea level has risen by 0.16 m between 1902 and 2015. Sea levels will continue to rise until 2100 and long thereafter.

For northern Sweden, land uplift largely compensates for the rise in sea level until 2100. Southern Sweden is much more affected by sea level rise, where the mean sea level could increase by more than 0.5 m by 2100. (Nerheim, Schöld, Persson, & Sjöström, 2018).

**Table 13** **Sea level rise with potential impacts**

| Sea level changes | Effect | Reference |
|---|---|---|
| Increase | Saltwater intrusion into estuaries | CEA |
| | Coastal erosion | CEA |
| Increase – variation – extremes | Coastal erosion and flooding | CEA |
| | Drift ice and ice walls | CEA |

Note: CEA = (CEA, 2020)

I Table 14 groups of potential climate indicators are presented. One of these is reported by SMHI (SMHI, 2022b), compare section 3.12. No other sources have been identified.

**Table 14** **Potential sea level climate indicators**

| No | Climate indicator | Source |
|---|---|---|
| S-1 | Average, minimum, and maximum values for years, seasons and months | |
| S-2 | High sea level events today and in the future | |
| S-3 | Future mean sea level | SMHI |

Note: SMHI = (SMHI, 2022b)

# 5 Initial Analysis of Climate Change that May Affect Dam Safety

Section 3 and 4 laid the foundation for the initial analysis of climate change that may affect dam safety that was carried out and presented in this section. The analysis is called initial because it has been qualitative and comprehensive and does not relate to any particular facility or activity.

## 5.1 METHODOLOGY

The literature review identified the methodology for climate risk analysis reported by GIZ & EURAC (GIZ & EURAC, 2017) (section 3.5).

In light of the fact that there is already a methodology developed for the analysis of risks related to dam safety (Energiföretagen, 2022b) the methodology was adapted, which was thus also simplified, to identify such risks linked to climate change. The risks identified can then be transferred to the regular work on risk analysis regarding dam safety.

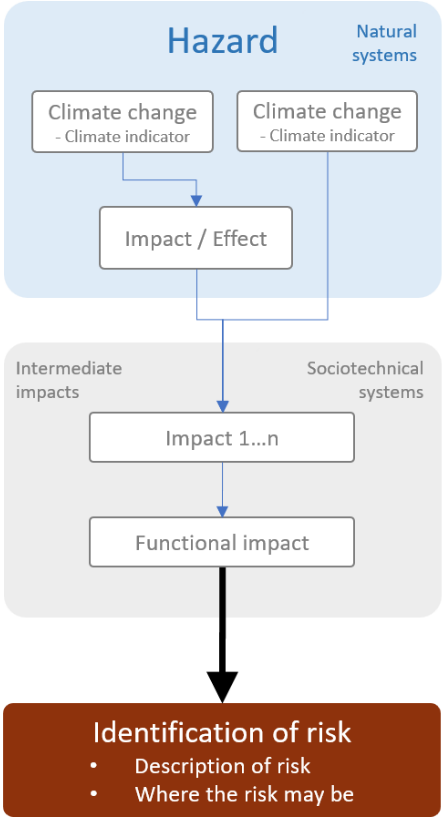

**Figure 5** **Impact chain for identifying risks to dam safety due to climate change**

According Figure 5 identified climate changes are considered as hazards (threats) that can lead to direct impacts on dam safety, or indirectly via impacts on natural systems that can lead to impacts on dam safety. It may also be the case that climate change indirectly affects dam safety via changes in sociotechnical systems.

An example of indirect impact on a natural system is that an increase in temperature in the atmosphere leads to warmer lakes and streams that lead to increased growth of vegetation or algae that can affect the possibilities for water level measurement, which in turn can affect dam safety.

An example of indirect impacts on a sociotechnical system is that more intense rainfall can lead to local flooding that can lead to the release of pollutants into watercourses that lead to an urgent need to change the flow that may conflict with dam safety.

These two descriptions are examples of two of the impact chains compiled. The impact chains that have been developed also constitute what is described in RIDAS as cause-and-effect context (Energiföretagen, 2022b).

For the developed impact chains, possible climate indicators were also listed with their sources that can be used to follow the identified changes.

In the impact chains, attempts were made to describe the functional impact, which formed the basis for sorting the impact chains on the main functions that contribute to dam safety, namely controlling, discharging and retaining (Energiföretagen, 2022a), as well as for the outside world and river flows.

River flows reported separately in section 4.6 were considered here as a hazard affected by climate change in temperature and precipitation.

## 5.2 DESCRIPTION OF IMPACT CHAINS

In the project, seventy or so impact chains were established and described. The impact chains were based on what can be described as the driving climate parameters temperature, precipitation, wind with their combinations, and sea level. Some impact chains describe a direct impact on the three main functions of dam safety: controlling, relieving and damping. Other impact chains describe an indirect impact on dam safety via changes in the operating environment and flows. The impact chains were grouped into the five areas of outside world, river flow, controlling, discharging and water retaining function.

The impact chains are reported in Attachment C:-1 to C-6. Developed impact chains were also characterized with regard to whether climate change refers to temporary conditions that can be described by variation and outliers, or lasting conditions that can be described by averages. The coherence between the impact chains that have been established is described by Figure 6 and Attachment C:-1.

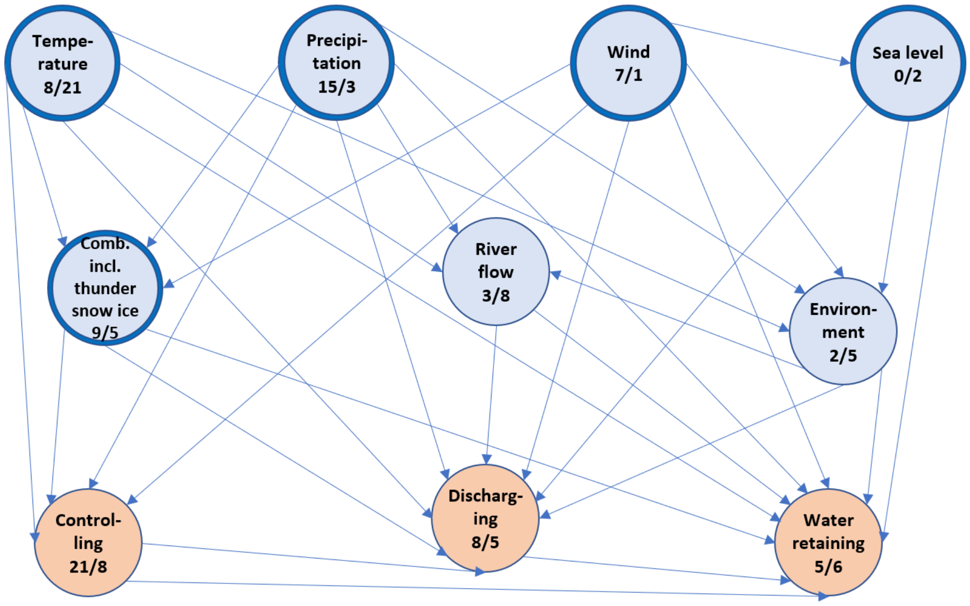

**Figure 6** **The relationships of the 71 impact chains – the five driving climate parameters with dark blue ring against external and flow impacts, as well as the main functions for dam safety. The first figure refers to temporary changes and the second to permanent changes.**

## 5.3 DESCRIPTION OF IMPACTS AND RISKS IDENTIFIED

A description of identified effects and risks is made in the following under the headings outside world, river flows, controlling, discharging and retaining.

### Outside world

The seven impact chains presented under the heading outside world refer to climate changes that lead to a change in the operating environment that in turn can affect dam safety. It can be noted that developed power chains have an impact on flows, which in turn can affect the relieving and damping function. Here are the effects of climate change such as:

- Floods that can lead to the discharge of pollutants into watercourses;
- High production of wind power locally can lead to rapid downregulation of hydropower generation locally as a result of grid constraints.
- Reduced water flow can lead to increased competition for water resources for recreational purposes, irrigation, etc.
- Warmer surface waters can lead to impacts on fish populations.
- Higher temperature leads to less need for heating and electrical energy.
- Higher temperatures during the summer and more heat waves can lead to the need for increased cooling in the community.

Common to these is that they can lead to changed conditions for the operation of hydropower, which can immediately or in the long term affect the water retaining and discharging functions and thus dam safety.

**River flows**

The eleven impact chains presented under the heading flows refer to climate changes that lead to impacts on flow conditions in watercourses, which in turn can affect dam safety. Here you will find:

- Precipitation in the form of rain and warm periods with snow melting during the winter can lead to an increased need for winter spillage.
- Increased duration of runoff or extreme runoff leading to full reservoirs.
- Increased duration of snow cover or extreme snowmelt leading to heavier spring floods.

Some possibilities from a dam safety point of view that link to decreasing flows were also presented.

**Controlling function**

For the impact chains – 29 – reported under the heading controlling, the idea was that they in turn can lead to poorer reliability in the discharging or water retaining function, which in turn affects dam safety. These impact chains are about:

- Effects leading to more vegetation around reservoirs and fouling on water level measurement equipment.
- Effects resulting in damage to power supply, buildings and equipment.
- Effects that lead to obstacles and prolong the time to get to the facilities due to local floods, landslides, windfalls, snow reefs and forest fires.
- Effects that can lead to increased absence of operating personnel such as illness or for other reasons.

**Discharging function**

The thirteen impact chains presented under the heading discharging function refer to those climate changes that may affect the need for discharge or have a direct technological impact on the discharge function that:

- Effects that can lead to sudden shutdown of the unit leading to urgent need for spillage.
- Effects leading to increased corrosion and thermal expansion in mechanical systems, including saltwater intrusion.
- Effects leading to disruption of power supply to spillway gates.
- Effects leading to erosion in watercourses, more debris, increased ice pressure or ice growth.

**Water retaining function**

The eleven impact chains presented under the heading water retaining function refer to climate changes that may affect the water retaining function as:

- Effects leading to damage to erosion control, dam crests, wood, concrete and mechanical structures, including torrential rain, wind impact, fouling, frost, ice and thermal expansion.

# 6 Discussion, Conclusions and Recommendations

This concluding section presents a discussion under the three headings:

- Some reflections on impacts, indicators and impact chains.
- Methodology for analysis and adaptation.
- Does climate change pose any new risks?

The project's conclusions and recommendations are then presented.

## 6.1 SOME LESSONS ON EFFECTS, INDICATORS, AND IMPACT CHAINS

One purpose of this project has been to identify climate changes that may affect dam safety. The results will form the basis for the Climate Committee's continued work. To what extent and how quickly identified changes may be realized is analyzed in other projects linked to the Climate Committee.

As can be seen from Table 3 there are about fifteen effects that were identified because of temperature changes. For these, it was also identified according to Table 4 a large number of potential climate indicators that can be used to track changes. For temperature, according to Figure 6 the largest number of impact chains has also been identified (29). Overall, it can be stated that temperature affects several different aspects related to dam safety. Temperature also shows a clear signal of change in the future climate.

According to Table 5 ten different effects are reported with links to precipitation and that most of these relate to flows. For these, a handful of groups with potential climate indicators were identified (Table 6). Figure 6 however, shows that many impact chains have been identified (18) and that a majority of these are linked to variation and extremes, i.e., to temporary changes. There are also relatively clear signals of changes in the future for precipitation, and all in all, it can be stated that precipitation is of great importance for flows in watercourses and the effects that these in turn cause.

As can be seen from Table 7 the impacts of wind identified are not very numerous (7) and the potential climate indicators few and unsourced (Table 8). Similarly, the number of impact chains is few (Figure 6). It is above all extreme or temporary conditions – read storm – that are important in this context. For wind, there are no clear signals of changes in the future. For conditions in the UK, changes in wind are considered to be less significant for dam safety (Atkins, 2013).

There are several (9) different combinations of the climate parameters temperature, precipitation and wind that have potential effects on dam safety (Table 9). They can also lead to effects of a very different nature. Table 10 generally refers to those relating to temperature and precipitation in terms of indicators, but also presents some specific ones.

As regards flows, Table 11 presents a handful of effects mainly linked to variations and extremes. There are several different potential climate indicators according to Table 12. For several of these, the Design Flood Conference has been cited as the source, which provides a basis for a recommendation to develop climate indicators that are linked to extreme flows.

Finally, identified climate changes, their impacts and functional impacts are linked to dam safety risks. Sometimes the connection to dam safety is clear in developed impact chains and sometimes it is not. After all, impact chains are considered to provide a good basis for the work that can be done to identify risks related to dam safety. Among the impact chains described, only a few will probably qualify for further analysis of risks for a specific facility.

## 6.2 METHODOLOGY FOR ANALYSIS AND ADAPTION

Several different initiatives relating to methodology for analysis and adaptation to climate change have been developed over the past 10 years.

The ability to handle high flows is central to dam safety and the Swedish hydropower industry was early to take climate change into account in the guidelines on design floods for dam facilities in 2007 (see section 3.1).

There is a consensus that climate change can be seen as hazards that entail or can lead to risks for various activities. The IPCC's conceptual framework now has risk at its core (IPCC, 2014), GIZ & EURAC follows in this track (GIZ & EURAC, 2017) and SIS base its standards for climate action on the starting points of the IPCC and GIZ & EURAC.

There is also a common understanding that analysis of risks from climate change can be integrated into companies' existing risk management processes, as put forward by the CEA (CEA, 2020). British Standards Institution (Johnstone, 2014) emphasizes that climate adaptation can be done within the framework of continuity management systems (SIS, 2019b), or other standardized working methods such as ISO 31000, ISO 14001 and ISO 9001. ICMM has recently laid the foundation for its members to integrate climate change related to dam safety into their regular operations under the Global Industry Standard on Tailings Management (ICMM, 2021b).

Although the Swedish guidelines for design floods for dam facilities (Svenska kraftnät, Energiföretagen, SveMin, 2022) contains clear guidance for a changing climate, so there is essentially no equivalent in the guidelines for dam safety RIDAS (Energiföretagen, 2022a) and GruvRIDAS (SveMin, 2021). A general reference to climate change is given in only one place in connection with guidance on design requirements.

In this project, an overall identification of risks to dam safety from a changing climate has been carried out. The identified risks (impact chains) can hopefully serve as a checklist of potential climate change and inspiration for mindsets for those who will perform analyses for specific facilities and operations. In this way, the results can be used in the companies' own risk analysis work, regardless of whether it concerns hydropower or mining operations and regardless of which system for analyzing risks is used. The methodology developed by Swedenergy for dam safety assessment (Energiföretagen, 2022b) and which includes analysis of dam safety risks is deemed appropriate to include also the risks identified related to climate change.

Impact chains are considered to have their value primarily in initial and general analyses of climate change, as in this project. However, they greatly simplify reality and to the extent that modelling of the corresponding conditions described in the impact chains is possible, it often provides a better alternative. A clear example is the modelling methodology applied in the Swedish design flood guidelines.

## 6.3 DOES CLIMATE CHANGE POSE ANY NEW RISKS ?

The Swedish Energy Agency stated already in 2009 (Statens energimyndighet, 2009) that challenges already exist with today's weather. Current annual variations are managed by the actors in the energy sector within the framework of the objectives and means at their disposal today. Climate change amplifies the threats. When it comes to future extreme weather events, the threats are not new, already today the energy supply is being subjected to tests in the form of extreme weather.

Similar ideas are put forward by the CEA, which argues that most of the risks that companies will identify through their adaptation processes will not be new but rather existing risks exacerbated by climate change (CEA, 2020).

The UK guidance notes that in many cases the focus of current adaptation measures involves an escalation over time with increased monitoring, preventive or remedial maintenance, to retrofitting and ultimately eventual decommissioning or change of use (Atkins, 2013).

A glance at the impact chains that have been developed also reveals that nothing decisively new has emerged, but rather that there is a high degree of recognition of the effects, impacts and risks identified.

A further aspect that can be highlighted in this context is that new materials and methods will be adapted to give a smaller climate footprint. Risks associated with this external factor are also worth analyzing further.

To conclude the discussion on whether climate change will pose some new risks that may affect dam safety, the aspect of increased uncertainty can be addressed. Climate change will affect different sectors of society and the energy system where hydropower is included in a way that we do not know today and thus add uncertainties that can potentially affect dam safety in different ways.

## 6.4 CONCLUSIONS AND RECOMMENDATIONS

Based on the accounting made above, the following conclusions can be drawn:

- Climate change in terms of dam safety is appropriately considered as risks.
- In the first instance, it is already known risks that may be exacerbated by climate change that are relevant for dam safety.
- With regard to the risk of extreme flows, the developed modelling methodology in the Swedish design flood guidelines provides a better basis than presented impact chains for analyses of changes due to the climate.
- Impact chains are considered valuable for identifying risks related to dam safety in initial and general analyses of climate change.

The following recommendations are relevant to make:

- Authorities and industry organizations are recommended to continue their efforts to monitor climate change and work to develop relevant climate indicators.
- Authorities and industry organizations are recommended to take climate change into account in their guidance and guidelines so that it is integrated as well as possible into the dam owners' regular dam safety work.
- Dam owners are recommended that the risks identified as a result of climate change are analyzed within the framework of the routines established for the regular dam safety work.
- For climate indicators that are specific to extreme flows, it is recommended that the Design Flood Conference take initiatives and establish working methods to develop such.

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# Attachment A: Terminology

| **Term** | **Explanation** |
|---|---|
| Impact chain | Method that provides an understanding of how a given hazard leads to direct or indirect impacts that spread through a system that is at risk (SIS, 2021). |
| Exposure | presence of people, activities, species or ecosystems, environmental functions, services, resources, infrastructure or economic, social, or cultural assets in places and situations that could be affected (SIS, 2019a). |
| Hazard | Potential source of harm (SIS, 2019a). |
| Indicator | Quantitative, qualitative or binary variable that can be measured or described in response to a defined criterion (SIS, 2019a). |
| Climate indicator | A climate indicator is a measure used to show changes or in a simple way make quite complex phenomena clear. It can consist of annual, seasonal or monthly values of various parameters that describe the climate. It can also be a combination of several parameters that together are important linked to, for example, activities in a specific sector (Nationella expertrådet för klimatanpassning, 2022). |
| Climate | Statistical description of weather using averages and variability for relevant quantities over a period varying from a few months to thousands or millions of years (SIS, 2019a). |
| Climate adaption | Adaption to climate change; Process of achieving adaptation to an actual or expected climate and its effects (SIS, 2019a). |
| Climate change | Change in climate that varies over a longer period, usually a few decades or even longer (SIS, 2019a). |
| Climate projection | Simulation of how the climate-related system may react in a scenario with certain future emissions or concentrations of greenhouse gases or aerosols, usually based on climate models (SIS, 2021). |
| Climate risk | Risks arising from climate change are the potential impacts that climate change can have on our societies and economies, as well as on the environment (SIS, 2021). |
| Sensitivity | The extent to which a system or species is affected, either negatively or positively, by the variability of one or more changes in climate (SIS, 2021). |
| Impact | Effect on natural and human systems (SIS, 2019a). |
| Risk | The effect of uncertainty (SIS, 2019a). |
| System | Group of interacting or interacting elements (SIS, 2021). |
| Vulnerability | Tendency or propensity to be adversely affected (SIS, 2019a). |

# Attachment B: List of potential climate impacts according to CEA

CEA (CEA, 2020) presents in its Appendix 3 a list of potential climate impacts for the electricity industry with the generation, transmission, and distribution sectors. The following presents the impacts that affect electricity production with hydropower and dam safety.

## 1. Changes in annual and/or seasonal patterns

### *a. Changes in mean annual and/or seasonal temperatures*

- Higher ambient temperature impacts electricity demand and associated pressures on the grid.
- Higher ambient temperature may entail increased maintenance requirements
- Higher ambient temperature may raise occupational health and safety issues (e.g., comfort levels and humidex readings) for maintenance and operating personnel.
- As summer peaks increase in certain jurisdictions, the balance of long-term energy contracts could be impacted (e.g., the mix of "diversity agreements" between winter-peaking and summer-peaking jurisdictions)).

### *b. Changes in water availability*

- About 60% of Canada's electricity production is hydroelectric, so major changes in water availability could potentially have significant supply, reliability, ancillary services, and planning impacts on the electricity system, especially in provinces where hydroelectric generation plays a central role.
- Hydro generation relies on a resource with competing uses: lakes and rivers are also used for fishing, recreation, transportation, water consumption, irrigation, etc. A change in water availability (e.g., an extended drought in the summer) may impact several uses at once, creating the potential for tensions and conflict.
- Hydroelectric operations may need to be modified to address increased risk of upstream or downstream flooding.

### *c. Changes in the type, timing, and intensity of precipitation*

- Wind/rain combination can cause damage to structures.
- Heavy precipitation may lead to flooding, resulting in oil/chemical spills.
- Potential to overburden storm drainage, leading to flash flooding (flooding of underground vaults and surface infrastructure) and related damage and outages (also see overland flooding discussed below).
- Potential to accelerate corrosion of steel components.

- Precipitation can cause changes in asset maintenance and cleaning needs (e.g., corrosion of transformers made with regular steel, rotting of wood structures due to increased moisture, etc.).
- May impact reservoir management.
- Freezing rain may cause ice accretion on overhead conductors.

### d. *Changes in runoff and ground conditions*

- Erosion can cause infrastructure damage.
- Saturation or destabilization of soil can impact slope stability, causing landslide risk.

### e. *Changes in extent and duration of snow cover (e.g., timing of spring melt), permafrost melt, and ice conditions (e.g., deepening of annual thaw)).*

- Changes to winter conditions in remote locations, including ice/thaw freezes, could raise maintenance and/or safety issues.
- Ground shifting, e.g., from thaw sensitivity and settlement of permafrost, may impact ground and integrity of structures—e.g., physical damage to asphalt and concrete; failure of dykes and containment; and compromised stability of pole foundations, power line towers, vaults, and cable chambers.
- Could impact on reservoir recharge and timing of recharge relative to summer peak demand.
- An increase in freeze-thaw cycles accelerates degradation.

## 2. Increasing frequency, intensity, and/or duration of extreme events

### a. *Heat waves*

- Bulk power system may be challenged in its ability to respond to peak load.
- Can cause risks to safety and comfort of workers.
- Reduced capacity of transformers may lead to faster transformer insulation breakdown, increasing maintenance needs, and shortening lifespans of power transformers and batteries.

### b. *Drought and wildfire*

- Can cause damage to infrastructure from wildfires and increased costs of maintenance.
- Can block access to equipment in need of response or repair.
- Can threaten employee and community safety, including primary threat from event and secondary threats from evacuation.

### c. *Wind events*

- Tornadoes could damage concrete poles and other permanent structures.

### d. *Major precipitation events, overland flooding, and storm surges*

- Flooding could jeopardize the backup generation that provides emergency power.
- Major rainfall could compromise the effective containment volume.
- Potential for landslides, erosion, and accumulation of mud and debris flow, leading to infrastructure damage and impacting slope stability.
- Can cause water treeing in electrical cables and cracking of cable insulation.
- Flash floods may result in accumulation of muck and debris in dam reservoir.
- Flooded basements or installations can lead to infrastructure damage—e.g., flooding of underground vaults and surface infrastructure; damage to batteries, switchgear, underground feeder assets, and low-lying substations; and related damage and outages.
- Can cause increased risks of landslides, coastal erosion, and infrastructure damage.
- Can compromise stability of foundations of towers and cause damage due to land movement.
- Saturation or destabilization of soil can impact slope stability, causing landslide risk.
- Can cause difficulty accessing equipment and impaired ability of repair crews to respond and restore service.
- Could hamper the ability of emergency teams to respond quickly and effectively.
- Can have impacts on infrastructure, including damage to drainage and sewage systems.

### e. *Ice storms and freezing rain*

- Ice accretion directly on towers, insulators, cable lines, and tower arms, can cause lines to drop or poles to break under the weight of ice.
- Tree and branch failure due to ice/snow accretion can lead to significant increase in tree contacts with lines, causing widespread infrastructure damage and power loss—e.g., snapping power lines and breaking or bringing down utility poles.
- Increased salt use causes equipment to corrode faster, leading to premature aging and the need for additional cleaning and maintenance.
- Can cause severe service impacts to customers.

### f. *Electrical storms*

- Increased potential for lightning strikes can result in equipment damage and/or disruption of supply.

## 3. Changes to ecosystem

### a. *Shifts in species range or reproductive patterns for plants and animals.*

- Changes to water temperature and levels may also impact fish populations, leading to regulatory changes for hydroelectric plants.

### b. *Pathogens, pests, and diseases*

- Vector-borne diseases can emerge or re-emerge, increasing exposure of outdoor workers to West Nile virus, Lyme disease, etc.
- Zoonotic (e.g., rodent-borne) diseases can emerge or re-emerge.
- Water-borne diseases can emerge or re-emerge.

### c. *Duration of growing season*

- May impact vegetation management—maintenance, operations, and reliability.

### d. *Sea level rise*

- Salt water has the potential to cause damage.
- Increased coastal erosion and flooding has the potential to cause large-scale loss of coastal property and infrastructure. A rise in sea level could impact facilities in coastal areas.
- Could impact current clearance distance between water and lines.
- Increased risk of flooding and erosion of coastal areas may exacerbate other hazards, such as ice ride-up and pile-up.

# Attachment C: Climate change impact chains that may affect dam safety

Attachment C-1: Impact chains – Number / distribution on the 5 climate parameters of temporary / lasting character – 1 (1)

| Climate parameter<br>Impact chain | Temperature | Precipitation | Wind | Sea level | Combination | Total |
|---|---|---|---|---|---|---|
|  | Temporary / Lasting | Temporary / Lasting | Temporary / Lasting | Temporary / Lasting | Temporary / Lasting | Temporary / Lasting |
| Outside world | - / 4 | 1 / - | 1 / - | - / - | - / 1 | 2 / 5 |
| River flows | 1 / 4 | 2 / 2 | - / - | - / - | - / 2 | 3 / 8 |
| Controlling | 3 / 7 | 8 / 1 | 4 / - | - / - | 6 / - | 21 / 8 |
| Discharging | 2 / 3 | 3 / - | - / - | - / 1 | 3 / 1 | 8 / 5 |
| Water retaining | 2 / 3 | 1 / - | 2 / 1 | - / 1 | - / 1 | 5 / 6 |
| Total | 7 / 22 | 15 / 3 | 7 / 1 | - / 2 | 9 / 5 | 39 / 32 |

# Attachment C-2: Climate change impact chains whose effects on the outside world may affect dam safety – 1 (1)

| HAZARD | | | INTERMEDIATE IMPACT | | | IDENTIFICATION OF RISK | |
|---|---|---|---|---|---|---|---|
| **Climate change** | **Climate indicator (Source)** | **Change / effect** | **Impact - 1** | **Impact - 2** | **Functional impact** | **Description of risk** | **Where the risk may be** |
| P > More and higher intensity downpours locally > | T - Days with extreme precipitation (>20mm/day) - year/season (SMHI climate scenario service - M) | > More frequent and more intense downpours lead to flooding > | > Floods can lead to the release of pollutants into watercourses > | > Pollutants in watercourses can lead to an urgent need to change the flow > | > Acute change in river flow can affect both water retaining and discharging function > | > Impact on water retaining / discharging function may increase the risk of failure > | > Watercourses close to potential pollutant discharges > |
| W > Prolonged strong wind > | T - Not identified | >> | > High production of wind power locally can lead to rapid downregulation of hydropower production locally as a result of grid restrictions > | > Rapid downregulation can lead to increased higher reservoir levels and/or the need for spillage > | > Rapid increase in reservoir levels/spillage can affect water retaining/dicharging function > | > Impact on water retaining / discharging function may increase the risk of failure > | > Dam facilities in areas with a lot of wind power > |
| C > Reduced river flow > | L - Discharge (average) - year/month (SMHI climate scenario service - H) | >> | > Reduced discharge can lead to increased competition for water resources for recreational purposes, irrigation, etc. > | > Increased competition for water resources can lead to changed conditions for regulation > | > Changed conditions can affect both water retaining and dicharging function > | > Impact on water retaining / discharging function may increase the risk of failure > | > Watercourses close to competing interests > |
| T > Higher temperature > | L - Air temperature - year/month (SMHI climate scenario service - H) | > Higher temperature leads to warmer water in lakes and water courses > | > Warmer surface waters can lead to impacts on fish populations > | > Impacts on fish populations can lead to changed conditions for regulation > | > Changed conditions can affect both water retaining and dicharging function > | > Impact on water retaining / discharging function may increase the risk of failure > | > Waters with low degree of regulation and valuable fish poulations > |
| T > Higher temperature > | L - Temperatur - year/season (SMHI climate scenario service - M) | >> | > Higher temperature leads to less need for heating and electrical energy > | > Less need for electrical energy can lead to higher reservoir levels > | > Changed conditions can affect both water retaining and dicharging function > | > Impact on water retaining / discharging function may increase the risk of failure > | > Dam facilities in general but especially those with lower discharge capacity requirements > |
| T > Higher temperature during summer ><br>> More heat waves > | L - Temperature - year/season<br>Max temperature - årstid<br>Longest heat wave - days > 25°C<br>Tropical days - year<br>(SMHI climate scenario service - M) | >> | > Higher temperatures during the summer and more heat waves can lead to the need for increased cooling in the community > | > Increased need for cooling during the summer can lead to the need for increased power with more units in operation > | > Increased need for more units in operation during the summer can lead to the need for maintenance in other seasons > | > Need for maintenance in other seasons affects maintenance operations > | > Dam facilities in general > |
| T > Higher temperature during summer ><br>> More heat waves > | L - Temperature - year/season<br>Max temperature - season<br>Longest heat wave - dygn > 25°C<br>Tropical days - year<br>(SMHI climate scenario service - M) | >> | > Higher temperatures during the summer and more heat waves can lead to the need for increased cooling in the community > | > Increased need for cooling during the summer can lead to increased energy demand > | > Increased energy demand can lead to lower reservoir levels > | Opportunity for dam safety | > Reservoirs throughout the country > |
| | H = Hydrology, M = Meteorology | | | | | | |

# Attachment C-3: Climate change chains whose effects on river flow may affect dam safety – 1 (1)

| HAZARD | | | INTERMEDIATE IMPACT | | | IDENTIFICATION OF RISK | |
|---|---|---|---|---|---|---|---|
| **Climate change** | **Climate indicator (Source)** | **Change / effect** | **Impact - 1** | **Impact - 2** | **Functional impact** | **Description of risk** | **Where the risk may be** |
| P > Extreme precipitation during winter > | T - Precipitation - month<br>(SMHI climate scenario service - H) | > Extreme precipitation during the winter leads to increased need for spill during the winter > | > The need for spillage during the winter can lead to the need for more gates than are adapted for winter operation > | > The need to take a gate into operation quickly can lead to difficulties > | > Difficulties to spill through spillways can lead to surcharge and overflow | > Surcharge and overflow increase risk of dam failure > | > Run-of-the-river power plants > |
| P > Extreme presipitation over large areas > | T - Frequence Haldo-rain - days > 90 mm<br>Volume 14-days precipitation<br>(Design Flood Conference) | > Extreme rainfall over large areas leads to extreme runoff > | > Extreme inflow can lead to full reservoirs and the need for spillage > | > The need for spill at full reservoirs can lead to capacity being exceeded > | > Insufficient discharge capacity can lead to surcharge and overflow > | > Surcharge and overflow increase risk of dam failure > | > Dam facilities in general, but especially those of moderate and minor social significance > |
| P > Increased precipitation > | L - Precipitation - year/month<br>Effective precipitation<br>(SMHI climate scenario service - H) | > Increased precipitation leads to increased inflow > | > Increased inflow can lead to increased reservoir filling > | > Increased reservoir filling can lead to spill and excess discharge capacity > | > Insufficient discharge capacity can lead to surcharge and overflow > | > Surcharge and overflow increase risk of dam failure > | > Dam facilities in general, but especially those of moderate and minor social significance > |
| P > ncreased precipitation during winter > | L - Precipitation - year/month<br>Effective precipitation<br>Snow water content (max)<br>(SMHI climate scenario service - H)<br>Follow-up of maximum snow covers<br>(Design Flood Conference) | > Increased precipitation during the winter leads to increased snow cover > | Increased snow cover can lead to higher spring floods > | > Higher spring flood can lead to increased reservoir filling > | > Increased reservoir filling increases risk of spill and insufficient discharge capacity > | > Surcharge and overflow increase risk of dam failure > | > Dam facilities in general, but especially those of moderate and minor social significance > |
| T > Higher temperature during spring > | T - Air temperature - year/month<br>Max temperature - season<br>(SMHI climate scenario service - HM) | > Higher temperatures in spring lead to more intense snow-melt > | > More intense snowmelt could lead to more intense spring flood > | > More intense spring floods can lead to increased reservoir filling, spillage and insufficient discharge capacity > | > Insufficient discharge capacity can lead to surcharge and overflow > | > Surcharge and overflow increase risk of dam failure > | > Dam facilities in general, but especially those of moderate and minor social significance > |
| T > Higher temperature > | L - Air temperature - year/month<br>(SMHI climate scenario service - H) | > Higher temperatures lead to melting of glaciers, which in the short term leads to inflow to the reservoirs > | > Increased inflow to water reservoirs can lead to increased reservoir filling in the short term > | > Increased reservoir filling in the short term can lead to spillage and insufficient discharge capacity > | > Insufficient discharge capacity can lead to surcharge and overflow in the short term > | > Surcharge and overflow increase risk of dam failure in the short term > | > Dam facilities in the rivers Luleälven and Skellefteälven > |
| T > Higher temperature > | L - Air temperature - year/month<br>(SMHI climate scenario service - H) | > Higher temperatures lead to melting of glaciers which in the longer term lead to lower base flows > | > Reduced inflow to water reservoirs can lead to reduced reservoir filling in the longer term > | > Reduced reservoir filling in the longer term can lead to less spill and less risk of insufficient discharge capacity > | >> | > Less spill and less risk of insufficient discharge capacity reduces the risk of dam failure in the longer term > | > Dam facilities in the rivers Luleälven and Skellefteälven > |
| T > Higher temperature during spring > | L - Air temperature - year/month<br>Max temperature - season<br>(SMHI climate scenario service - HM)<br>Spring flood start<br>(Design Flood Conference) | > Higher temperature in spring leads to earlier snow-melt > | > Earlier snowmelt could lead to earlier spring floods > | > Earlier spring floods may lead to earlier reservoir filling > | >> | > Earlier spring floods are neither a risk nor an opportunity > | >> |
| T > Higher temperature during spring > | L - Air temperature - year/month<br>Max temperature - season<br>(SMHI climate scenario service - HM) | > Higher temperature in spring leads to earlier snow-melt > | > Earlier snowmelt leads to reduced maximum snow cover > | > Reduced maximum snow cover can lead to reduced spring flood > | > Reduced spring flood can lead to reduced reservoir filling > | > Reduced reservoir filling reduces the risk of dam failure > | > Dam facilities in smaller water courses > |
| C > Longer and more dry periods with heat waves > | L - Longest dry spell - days<br>Number of dry days - days<br>Longest heat wave - days > 25°C<br>(SMHI climate scenario service - M) | > Longer dry periods and heat waves lead to increased evaporation and low runoff > | > Low inflow for a long time can lead to reduced reservoir filling > | >> | >> | > Reduced reservoir filling reduces the risk of dam failure > | > Dam facilities in smaller water courses > |
| C > Lower river flow > | L - Vattenföring (medel) - år/månad<br>(SMHI climate scenario service - H) | >> | > Reduced water flow can lead to reduced reservoir filling > | >> | >> | > Reduced reservoir filling reduces the risk of dam failure > | > Dam facilities in smaller water courses > |

H = Hydrology, M = Meteorology

# Attachment C-4: Climate change impact chains that may affect the controlling function – 1 (2)

| HAZARD | | | INTERMEDIATE IMPACT | | | IDENTIFICATION OF RISK | |
|---|---|---|---|---|---|---|---|
| **Climate change** | **Climate indicator (Source)** | **Change / effect** | **Impact - 1** | **Impact - 2** | **Functional impact** | **Description of risk** | **Where the risk may be** |
| P > More frequent and more intense downpours locally > | T - Days with extreme precipitation (>20mm/day) - year/season (SMHI climate scenario service - M)<br>Frequence Haldo-rain (>120 mm/24 h) (Design Flood Conference) | >> | > More frequent and more intense downpours can lead to water treeing into cables, cable cabinets and cable paths > | > More shorted or failed power lines can lead to more disruptions in regular power supply > | > More power disruptions can lead to reduced reliability of the controlling function > | > Worse reliability in the controlling function can lead to late, incorrect or missing operational measures as can affect the water retaining and discharge function > | |
| P > More frequent and more intense downpours locally > | T - Days with extreme precipitation (>20mm/day) - year/season (SMHI climate scenario service - M)<br>Frequence Haldo-rain (>120 mm/24 h) (Design Flood Conference) | >> | > More frequent and more intense downpours can lead to poorer stability in the foundations of power line poles, which can lead to short circuits or breakdowns > | > More shorted or failed power lines can lead to more disruptions in regular power supply > | > More power disruptions can lead to reduced reliability of the controlling function > | | |
| C > Freezing rain and ice storms more frequent and intense | T - Not identified | > Freezing rain and ice storms lead to ice formation > | > Icing on towers, insulators, power lines and tower arms can cause power lines to short-circuit or breakdown more often > | > More shorted or failed power lines can lead to more disruptions in regular power supply > | > More power disruptions can lead to reduced reliability of the controlling function > | | |
| C > More and heavier snowfall > | T - Not identified | > More frequent and heavier snowfalls lead to subsequent icing on branches and trees > | > Icing on branches and trees can cause power lines to short-circuit or breakdown more often > | > More shorted or failed power lines can lead to more disruptions in regular power supply > | > More power disruptions can lead to reduced reliability of the controlling function > | | |
| W > More and stronger storms > | T - Not identified | > More and stronger storms lead to more windfalls > | > More windfalls can lead to power lines shorting or failing more often > | > More shorted or failed power lines can lead to more disruptions in regular power supply > | > More power disruptions can lead to reduced reliability of the controlling function > | | |
| W > More and stronger storms > | T - Not identified | >> | > More and stronger storms can cause more damage to buildings, masts and poles > | > More damage to masts and poles can lead to more disruptions in overhead data and telecommunications > | > More disruptions in data and telecommunications can lead to poorer reliability of the controlling function > | | |
| P > More frequent and more intense downpours locally > | T - Days with extreme precipitation (>20mm/day) - year/season (SMHI climate scenario service - M)<br>Frequence Haldo-rain (>120 mm/24 h) (Design Flood Conference) | >> | > More frequent and more intense downpours can lead to water treeing into cables, cable cabinets and cable paths > | > Water treeing into cables can lead to disruption of data and telecommunications > | > More disruptions in data and telecommunications can lead to poorer reliability of the controlling function > | | |
| P > More frequent and more intense downpours locally > | T - Days with extreme precipitation (>20mm/day) - year/season (SMHI climate scenario service - M)<br>Frequence Haldo-rain (>120 mm/24 h) (Design Flood Conference) | >> | > More frequent and more intense downpours can lead to damage to facilities and equipment > | >> | > More damage to plant and equipment can lead to reduced reliability of the controlling function > | | |
| C > More thunder-storms with lightning > | T - Not identified | >> | > More lightning storms can lead to more damage to facilities and equipment > | >> | > More damage to plant and equipment can lead to reduced reliability of the controlling function > | | |
| C > More thunder-storms with lightning > | T - Not identified | > More lightning thunderstorms lead to more forest fires > | > More forest fires can lead to more damage to facilities and equipment > | >> | > More damage to plant and equipment can lead to reduced reliability of the controlling function > | | |
| T > Longer and more dry periods with heat waves > | T - Longest dry period - days<br>Number of dry days - days<br>Longest heat wave - days > 25°C (SMHI climate scenario service - M) | > Longer and more dry periods with heat waves lead to more forest fires > | > More forest fires can lead to more damage to facilities and equipment > | >> | > More damage to plant and equipment can lead to reduced reliability of the controlling function > | | |
| T > Higher temperature > > More heatwaves > | T - Temperature - year/month<br>Longest dry period - days > 25°C<br>Tropical days - year (SMHI climate scenario service - M) | >> | > Higher temperature and heat waves can lead to faster insulation degradation, lower capacity and shorter life of transformers, batteries and other electrical components > | > Shorter service life of electrical components can lead to impaired or loss of function > | > More damage to plant and equipment can lead to reduced reliability of the controlling function > | | |
| T > More heatwaves > | T - Longest dry period - days > 25oC<br>Tropical days - year (SMHI climate scenario service - M) | >> | > Extreme temperatures can lead to more difficult working conditions for staff > | > More difficult working conditions may require more time for recovery > | > More time for recovery can lead to late or missing operational measures > | | |
| P > More frequent and more intense downpours locally > | T - Days with extreme precipitation (>20mm/day) - year/season (SMHI climate scenario service - M)<br>Frequence Haldo-rain (>120 mm/24 h) (Design Flood Conference) | >> | > More frequent and more intense downpours can lead to more difficult working conditions for staff > | > More difficult working conditions may require more time for > | > More time for recovery can lead to late or missing operational measures > | | |
| P > More frequent and more intense downpours locally > | T - Days with extreme precipitation (>20mm/day) - year/season (SMHI climate scenario service - M)<br>Frequence Haldo-rain (>120 mm/24 h) (Design Flood Conference) | >> | > More frequent and more intense downpours can lead to flooding that makes access to backup and emergency equipment difficult > | > Difficult access to backup and emergency equipment may result in more time being required > | > More time to get to facilities and equipment can lead to reduced reliability of the controlling function > | | |

# Attachment C-4: Climate change impact chains that may affect the controlling function – 2 (2)

| HAZARD | | | INTERMEDIATE IMPACT | | | IDENTIFICATION OF RISK | |
|---|---|---|---|---|---|---|---|
| **Climate change** | **Climate indicator (Source)** | **Change / effect** | **Impact - 1** | **Impact - 2** | **Functional impact** | **Description of risk** | **Where the risk may be** |
| **P** > More frequent and more intense downpours locally > | **T** - Days with extreme precipitation (>20mm/day) - year/season<br>(SMHI climate scenario service - M)<br>Frequence Haldo-rain (>120 mm/24 h)<br>(Design Flood Conference) | > More frequent and more intense downpours lead to saturated ground > | > Saturated soil can lead to poorer stability in slopes and slopes with erosion and landslides at access roads that can lead to poorer accessibility > | > Poor accessibility on access roads can lead to more time being required to get to facilities and equipment > | > More time to get to facilities and equipment can lead to reduced reliability of the controlling function > | ><br>Worse reliability<br>in the<br>controlling function<br>can<br>lead<br>to<br>late,<br>incorrect<br>or<br>missing<br>operational measures<br>as<br>can<br>affect<br>the<br>water retaining<br>and<br>discharge function<br>> | |
| **P** > Increased rainfall > | **L** - Precipitation - year/month<br>Soil moisture (average)<br>Surface runoff (average)<br>(SMHI klimatscenariotjänst - H) | > Increased rainfall leads to saturated soil > | > Saturated soil can lead to poorer stability in slopes and slopes with erosion and landslides at access roads that can lead to poorer accessibility > | > Poor accessibility on access roads can lead to more time being required to get to facilities and equipment > | > More time to get to facilities and equipment can lead to reduced reliability of the controlling function > | | |
| **P** > More frequent and more intense downpours locally > | **T** - Days with extreme precipitation (>20mm/day) - year/season<br>(SMHI climate scenario service - M)<br>Frequence Haldo-rain (>120 mm/24 h)<br>(Design Flood Conference) | > More frequent and more intense downpours lead to local flooding > | > Local flooding on access roads can lead to poorer accessibility > | > Poor accessibility on access roads can lead to more time being required to get to facilities and equipment > | > More time to get to facilities and equipment can lead to reduced reliability of the controlling function > | | |
| **T** > Higher temperature during winter > | **L** - Cold days (max<-7°C)<br>Days with frost (< 0°C)<br>(SMHI climate scenario service - M) | > Higher temperatures during the winter lead to less cold amount and reduced frost > | > Reduced frost can lead to more damage to access roads and poorer accessibility > | > Poor accessibility on access roads can lead to more time being required to get to facilities and equipment > | > More time to get to facilities and equipment can lead to reduced reliability of the controlling function > | | |
| **T** > Higher temperature during winter > | **L** - Cold days (max<-7oC)<br>Days with frost (< 0oC)<br>(SMHI climate scenario service - M) | > Higher temperatures during the winter lead to less cold amount and reduced frost > | > Reduced frost can lead to more windfalls over access roads and poorer accessibility > | > Poor accessibility on access roads can lead to more time being required to get to facilities and equipment > | > More time to get to facilities and equipment can lead to reduced reliability of the controlling function > | | |
| **W** > More and stronger storms > | **T** - Not identified | >> | > More and stronger storms can lead to more windfalls over access roads and poorer accessibility > | > Poor accessibility on access roads can lead to more time being required to get to facilities and equipment > | > More time to get to facilities and equipment can lead to reduced reliability of the controlling function > | | |
| **W** > More and stronger storms > | **T** - Not identified | > More and stronger storms lead to an increase in snow reefs > | > Snow reefs on access roads can lead to poorer accessibility > | > Poor accessibility on access roads can lead to more time being required to get to facilities and equipment > | > More time to get to facilities and equipment can lead to reduced reliability of the controlling function > | | |
| **C** > More thunder-storms with lightning > | **T** - Not identified | > More lightning thunderstorms lead to more forest fires > | > More forest fires on access roads can lead to poorer accessibility > | > Poor accessibility on access roads can lead to more time being required to get to facilities and equipment > | > More time to get to facilities and equipment can lead to reduced reliability of the controlling function > | | |
| **C** > More thunder-storms with lightning > | **T** - Not identified | > More lightning thunderstorms lead to more forest fires > | > Forest fires can lead to affected communities and the need for evacuation > | > Evacuation can result in employees not being able to come to work > | > Increased absenteeism can lead to increased strain on personnel on duty which can lead to poorer reliability of the controlling function > | | |
| **T** > Higher temperature > | **L** - Air temperature - year/season<br>(SMHI climate scenario servic - M) | > Higher temperature leads to warmer water in lakes and streams > | > Warmer surface water can lead to an increase in vector-borne (disease-carrying insects, etc.) diseases > | > Vector-borne diseases (such as Lyme disease, West Nile virus, etc.) can lead to increased sick leave > | > Increased absenteeism can lead to increased strain on personnel on duty which can lead to poorer reliability of the controlling function > | | |
| **T** > Higher temperature > | **L** - Air temperature - year/season<br>(SMHI climate scenario servic - M) | > Higher temperature leads to warmer water in lakes and streams > | > Warmer surface waters may lead to increase zoonotic (animal to human) diseases such as flus > | > More flus can lead to increased sick leave > | > Increased absenteeism can lead to increased strain on personnel on duty which can lead to poorer reliability of the controlling function > | | |
| **T** > Higher temperature > | **L** - Air temperature - year/season<br>(SMHI climate scenario servic - M) | > Higher temperature leads to warmer water in lakes and streams > | > Warmer surface water can lead to an increase in waterborne diseases such as gastrointestinal infections > | > More gastrointestinal infections can lead to increased sick leave > | > Increased absenteeism can lead to increased strain on personnel on duty which can lead to poorer reliability of the controlling function > | | |
| **T** > Higher temperature > | **L** - Air temperature - year/season<br>(SMHI climate scenario servic - M) | > Higher temperature leads to longer growing season > | > Longer growing season can lead to more vegetation on and around dams > | > More vegetation on and around ponds can make it difficult to detect weaknesses > | > Difficult detection of weaknesses can lead to poorer reliability of the controlling function > | | |
| **T** > Higher temperature > | **L** - Air temperature - year/season<br>(SMHI climate scenario servic - M) | > Higher temperatures lead to warmer lakes and streams which can lead to more invasive species, increased vegetation and algae growth > | > Invasive species, vegetation and algae growth can lead to fouling of equipment below and at the surface of the water > | > Fouling at/on gauges can lead to incorrect water level measurement > | > Incorrect water level measurement may result in poorer reliability of the controlling function > | | |
| | H = Hydrology. M = Meteorology | | | | | | |

# Attachment C-5: Climate change impact chains that may affect the discharging function – 1 (1)

| HAZARD | | | INTERMEDIATE IMPACT | | | | IDENTIFICATION OF RISK | |
|---|---|---|---|---|---|---|---|---|
| **Climate change** | **Climate indicator (Source)** | **Change / effect** | **Impact - 1** | **Impact - 2** | **Impact - 3** | **Functional impact** | **Description of risk** | **Where the risk may be** |
| **T** > Higher temperature during winter > | **L** - Air ttemperature - year/month<br>(SMHI climate scenario service - H) | > Higher temperature leading to later icing that can lead to frazil ice and ice plugs > | > Frazil ice and ice plugs can lead to the stoppage of aggregates and downregulation > | > Stopping the unit can lead to the need for spillage through spillways > | > Spill in winter can lead to ice growth on channel walls leading to reduced stability > | > Reduced stability of channel walls can lead to breakdown of discharge function > | > Failure of discharge function can lead to downstream erosion that can lead to dam failure > | > Run-of-the-river power plants in cold regions > |
| **T** > Higher temperature > | **L** - Temperature - year/season<br>(SMHI climate scenario service - M) | > Higher temperatures leading to warmer water in lakes and streams that can lead to more invasive species, increased vegetation and algae growth > | > Fouling at water intake can lead to impaired cooling and the need to stop the unit > | > Stopping the unit can lead to the need for spillage through spillways > | > Spill through spillways increases wear on mechanical systems and degradation of waterways > | > Degradation of spillways and waterways can lead to reduced reliability and loss of function > | > Late or loss of function can lead to surcharge and overflow > | > Run-of-the-river power plants in warm regions > |
| **T** > More heat waves > | **T** - Longest heat wave - days > 25°C<br>Tropical days - year<br>(SMHI climate scenario service - M) | >> | > More heat waves can lead to thermal expansion in mechanical systems such as spillways etc > | > Thermal expansion can lead to inertia in mechanical systems that can lead to spillways wedged > | > Inertia and wedged can lead to poorer reliability of the discharge function > | > Poor reliability of the discharge function can lead to late or loss of function > | > Late or loss of function can lead to surcharge and overflow > | >> |
| **T** > Higher temperature ><br>> More heat waves > | **T** - Air temperature - year/month<br>Longest heat wave - days > 25°C<br>Tropical days - years<br>(SMHI climate scenario service - HM) | >> | > Higher temperatures and more heat waves can lead to faster insulation degradation, lower capacity and shorter lifespan of transformers, batteries and other electrical components > | > Faster breakdown of electrical components can lead to poorer reliability of the discharge function > | | > Poor reliability of the discharge function can lead to late or loss of function > | > Late or loss of function can lead to surcharge and overflow > | > Dam facilities in central Sweden > |
| **T** > Increased daily variation in temperature during winter > | **L** - Daily amplitude temp.- year/season<br>(SMHI climate scenario service - M) | > Increased diurnal variation in temperature during the winter leads to ice cover swelling > | > Swelling ice cover can lead to increased ice pressure on spillway gates and equipment > | > Increased ice pressure on spillway gates and equipment can lead to buckling or damage > | > Buckling on spillway hatches and damage to equipment can lead to poorer reliability of the discharge function > | > Poor reliability of the discharge function can lead to late or loss of function > | > Late or loss of function can lead to surcharge and overflow > | > Dam facilities in northern Sweden > |
| **C** > Increased humidity > | **L** - Air temperature - year/month<br>Precipitation - year/month<br>(SMHI climate scenario service - H) | > Higher temperature and increased precipitation lead to increased humidity > | > Increased humidity can lead to increased corrosion in mechanical systems > | > Increased corrosion can lead to increased degradation of mechanical systems > | > Degradation of mechanical systems can lead to reduced reliability > | > Poor reliability of the discharge function can lead to late or loss of function > | > Late or loss of function can lead to surcharge and overflow > | >> |
| **P** > More frequent and more intense downpours locally > | **T** - Days with extreme precipitation (>20mm/day) - year/season<br>(SMHI climate scenario service - M)<br>Follow-up Haldo-rain (>120 mm/24 h)<br>(Design Flood Conference) | >> | > More frequent and more intense downpours can lead to erosion in watercourses, estuaries and beach areas around the reservoir > | > Erosion in watercourses, estuaries and riparian areas can lead to more debris in the reservoir > | > More debris in the reservoir can lead to poorer reliability in the discharge function > | > Poorer reliability of the discharge function may result in a loss of function > | > Late or loss of function can lead to surcharge and overflow > | > Dam facilities with a history of debris > |
| **P** > More frequent and more intense downpours locally > | **T** - Days with extreme precipitation (>20mm/day) - year/season<br>(SMHI climate scenario service - M)<br>Follow-up Haldo-rain (>120 mm/24 h)<br>(Design Flood Conference) | >> | > More frequent and more intense downpours can lead to water treeing into cables, cable cabinets and cable paths > | > Water treeing into cables can lead to disruption of power supply > | > Power disruption may result in reduced reliability of the discharge function > | > Poorer reliability of the discharge function may result in a loss of function > | > Late or loss of function can lead to surcharge and overflow > | > Older power stations > |
| **P** > More frequent and more intense downpours locally > | **T** - Days with extreme precipitation (>20mm/day) - year/season<br>(SMHI climate scenario service - M)<br>Follow-up Haldo-rain (>120 mm/24 h)<br>(Design Flood Conference) | > More frequent and more intense downpours lead to local flooding > | > Local flooding can lead to water flow into access tunnels and other underground facilities > | > Water flow into access tunnels and other underground facilities can lead to the blockage of aggregates > | > Stopping of units can lead to the need for spill through spillways that can lead to increased degradation in mechanical systems and waterways > | > Degradation in mechanical systems and waterways can lead to reduced reliability and loss of function > | > Late or loss of function can lead to surcharge and overflow > | > Underground stations > |
| **C** > Freezing rain and ice storms more frequent and more intense > | **T** - Not identified | >> | > Freezing rain and ice storms may lead to icing on discharge devices > | > Icing on discharge devices may lead to poorer reliability of discharge function > | >> | > Poor reliability of the discharge function can lead to late or loss of function > | > Late or loss of function can lead to surcharge and overflow > | >> |
| **C** > More lightning thunderstorms > | **T** - Not identified | >> | > Increased frequency of lightning storms can lead to regular power being knocked out > | > Knocked out regular power supply can lead to poorer reliability of the discharge function > | >> | > Poor reliability of the discharge function can lead to late or loss of function > | > Late or loss of function can lead to surcharge and overflow > | > Dam facilities without redundancy in grid connection > |
| **S** > Higher sea levels > | **L** - Sea level by municipality<br>(SMHI - future mean sea level) | > Higher sea levels leading to salty seawater in the lower parts of watercourses > | > Higher sea levels can cause salty seawater to reach coastal dam facilities > | > Salty seawater at dam facilities can lead to increased degradation and corrosion > | > Increased corrosion may lead to poorer reliability of discharge devices > | > Poor reliability of the discharge function can lead to late or loss of function > | > Late or loss of function can lead to surcharge and overflow > | > Dam facilities at the bottom of watercourses > |
| **C** > Higher sea levels with strong onshore winds > | **T** - Sea level by municipality<br>(SMHI - future mean sea level)<br>- Not identified | > Higher sea levels leading to flooding in the lower parts of watercourses > | > Flooding in the lower parts of watercourses may lead to the need for reduced discharge > | > Reduced discharge can lead to increased reservoir filling upstream > | >> | >> | > Surcharge and overflow increase the risk of dam failure > | >> |

# Attachment C-6: Climate change chains that may affect the water retaining function – 1 (1)

| HAZARD | | | INTERMEDIATE IMPACT | | | IDENTIFICATION OF RISK | |
|---|---|---|---|---|---|---|---|
| **Climate change** | **Climate indicator (Source)** | **Change / effect** | **Impact - 1** | **Impact - 2** | **Functional impact** | **Description of risk** | **Where the risk may be** |
| **W** > Change of prevailing wind direction > | **L** - Not identified | > Prevailing wind direction changes > | > Changing wind direction can lead to increased damage to erosion protection > | > Damage to erosion protection can lead to further damage development in the event of surcharge and overflow > | > Damage development from surcharge and overflow can lead to erosion in dam crests > | > Erosion in dam crests increases the risk of dam failure > | > Dam facilities with wide reservoirs, narrow crest and small freeboard > |
| **P** > More frequent and more intense local downpours > | **T** - Days with extreme precipitation (>20mm/day) - year/season (SMHI climate scenario service - M)<br>Follow-up Haldo-rain (>120 mm/24 h) (Design Flood Conference) | >> | > More frequent and more intense local downpours can lead to damage to dam crests and abutments > | > Damage to dam crests and connections can lead to further damage development in the event of surcharge and overflow > | > Damage development from surcharge and overflow can lead to erosion in dam crests > | > Erosion in dam crests increases the risk of dam failure > | > Dam facilities with narrow crest and small freeboard > |
| **W** > More and stronger storms > | **T** - Not identified | > More and stronger storms lead to increased wave formation more often > | > Stronger wave formation more often can lead to increased damage to erosion protection at both high and low rlevels of the dam > | > Damage to erosion protection can lead to further damage development in the event of surcharge and overflow > | > Damage development from surcharge and overflow can lead to erosion in dam crests > | > Erosion in dam crests increases the risk of dam failure > | > Dam facilities with narrow crest and small freeboard > |
| **W** > More and stronger storms > | **T** - Not identified | > More and stronger storms lead to increased set-up more often > | > Increased wind set-up more often can lead to higher magazine positions > | > Increased wind set-up more often can lead to further damage development in the event of surcharge and overflow > | > Damage development from surcharge and overflow can lead to erosion in dam crests > | > Erosion in dam crests increases the risk of dam failure > | > Dam facilities with narrow crest and small freeboard > |
| **T** > Higher temperature > | **L** - Temperature - year/season (SMHI climate scenario service - M) | > Higher temperature leads to longer growing season > | > Longer growing season can lead to more vegetation on and around dam facilities > | > More vegetation on and around dam facilities can lead to increased growth of roots > | > Increased growth of roots can lead to reduced density and stability > | > Reduced water tightness and stability increase the risk of dam failure > | > Dam facilities with narrow crest and small freeboard > |
| **T** > Higher temperature > | **L** - Temperature - year/season (SMHI climate scenario service - M) | > Higher temperature leads to longer growing season > | > Longer growing season can lead to more growth on concrete structures > | > More fouling on concrete structures can lead to increased degradation > | > Increased degradation leads to reduced water tightness and stability of concrete structures > | > Reduced water tightness and stability increase the risk of dam failure > | > Older concrete structures with a history of fouling > |
| **T** > More zero pass-throughs > | **L** - Zero pass-throughs (days) (SMHI climate scenario service - M) | > More zero pass-throughs lead to an increase in freezing and thawing cycles > | > More cycles of freezing and thawing can lead to increased frost bursting > | > Increased frost bursting can lead to increased degradation > | > Increased degradation leads to reduced water tightness and stability of concrete structures > | > Reduced water tightness and stability increase the risk of dam failure > | > Older concrete structures with a history of frost bursting > |
| **T** > Increased diurnal variation in temperature > | **T** - Daily amplitude temp. - year/season (SMHI climate scenario service - M) | > Increased diurnal variation in temperature during the winter leads to ice cover swelling > | > Swelling ice sheets can lead to increased ice pressure on water retaining structures and equipment > | > Increased ice pressure on water retaining structures and equipment can lead to cracking and buckling > | > Cracking in concrete structures can lead to reduced water tightness and stability > | > Reduced water tightness and stability increase the risk of dam failure > | > Dam facilities with slender concrete structures > |
| **T** > More heat waves > | **T** - Longest heat wave - days > $25^{\circ}$C<br>Tropical days - years (SMHI climate scenario service - M) | >> | > Extreme temperature can lead to thermal expansion and stresses in concrete structures > | > Stresses in concrete structures can lead to cracking > | > Cracking in concrete structures can lead to reduced water tightness and stability > | > Reduced water tightness and stability increase the risk of dam failure > | > Dam facilities with slender concrete structures > |
| **C** > Increased humidity > | **L** - Temperature - year/season<br>Precipitation - year/season (SMHI climate scenario service - M) | > Higher temperature and increased precipitation lead to increased humidity > | > Increased humidity can lead to increased rotting of wooden structures > | >> | > Increased rotting of wooden structures can lead to reduced durability, tightness and stability > | > Reduced water tightness and stability increase the risk of dam failure > | > Dam facilities with slender concrete structures > |
| **S** > Higher sea levels > | **L** - Sea level by municipality (SMHI - future mean sea level) | > Higher sea levels lead to salty seawater reaching coastal dam facilities > | > Salty seawater at dam facilities can lead to increased degradation and corrosion > | >> | > Increased degradation and corrosion of concrete structures can lead to reduced durability, tightness and stability > | > Reduced water tightness and stability increase the risk of dam failure > | > Dams at the bottom of watercourses > |

# IMPACT OF CLIMATE CHANGE ON DAM SAFETY

Climate change is best regarded as risks that are integrated into regular dam safety work. Impact chains have been used to identify risks to dam safety at a general level that can form the basis for further analyses for specific facilities and operations.

In the first instance, it is already known risks that may be exacerbated by climate change that are relevant in terms of dam safety. The work to monitor climate change that may have an impact on dam safety needs to continue. As part of this, more climate indicators need to be developed.

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