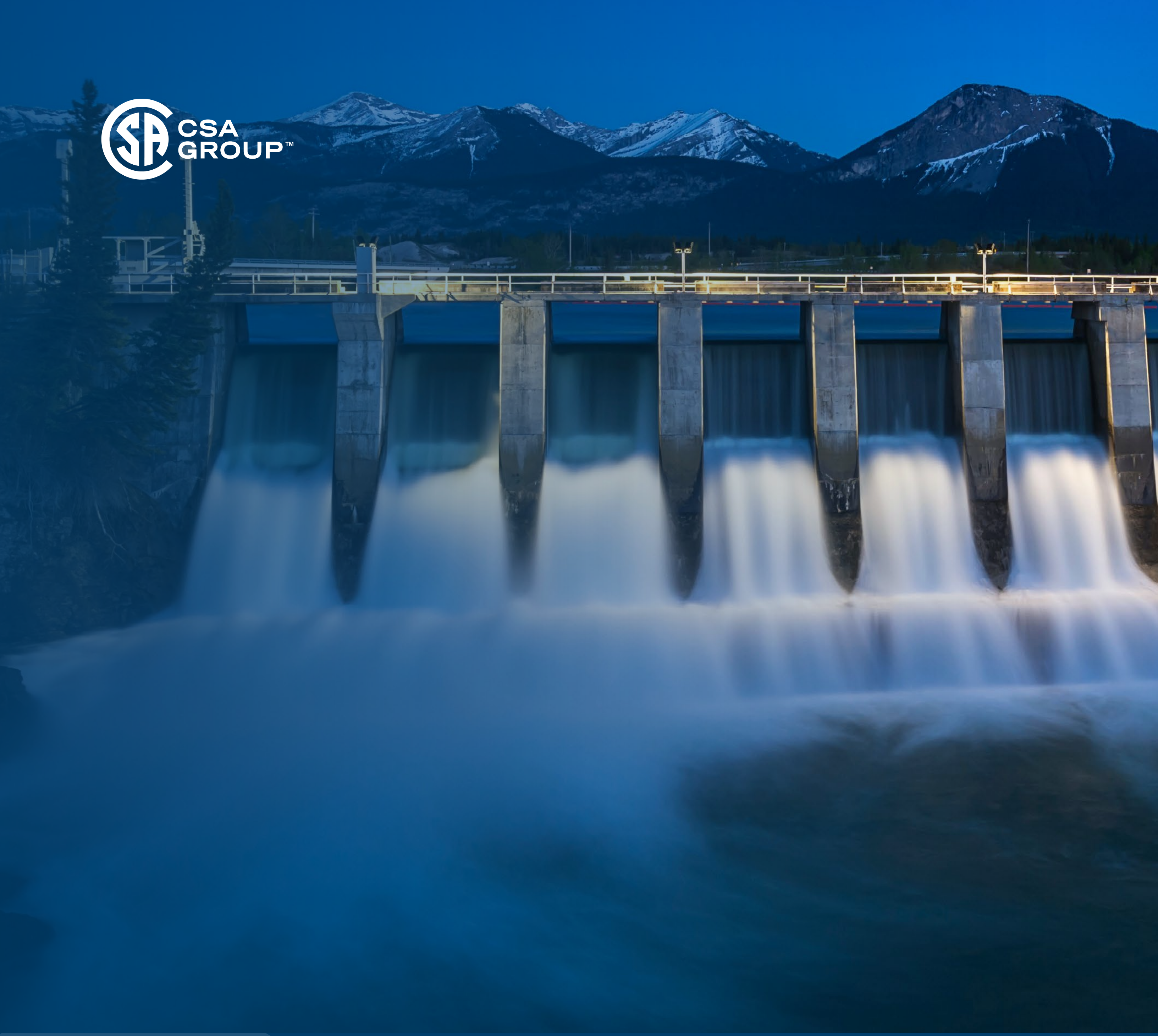

STANDARDS RESEARCH

Climate Change Adaptation for Dams

A Review of Climate Vulnerabilities, Adaptation Measures, and Opportunities for Growth in the Canadian Dams Context

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Executive Summary

Climate change in Canada is expected to bring hotter, wetter, and wilder weather, which could impact dams across the country. In the dam industry, existing dam safety and operations guidelines and regulations do not specifically address how to adapt dams to climate change. Therefore, the impact climate change may have on dams, the need to act, and the path forward to address climate changes to dams is not yet well understood.

This research sought to better understand the climate risks impacting dams in Canada; the existing standards, guidelines, and best practices that address climate change adaptation for dams; what is currently being done to address the issue; and what solutions are needed. This is done through a literature review, stakeholder interviews and a workshop, and validated by an advisory panel of industry experts.

The literature review found that major climate risks to dams include changes to the hydrologic cycle potentially impacting design loads and Inflow Design Floods (IDFs); changes to operations and maintenance to respond to different operating needs, frequencies and conditions; changes to foundations due to melting permafrost; issues with site access due to storms and extreme weather events; additional stress on water supply impacting dam operations and functionality; impacts to hydropower generation due to a less predictable hydrologic cycle; and more. The review found that guidance documents on how to adapt infrastructure to climate change are often not applicable to the dams context. Some guidance at the international level on climate adaptation for dams exists but remains high level and difficult to interpret to the watershed-specific context. Other regional guidance exists but similarly lacks detail or applicability to dams across the country.

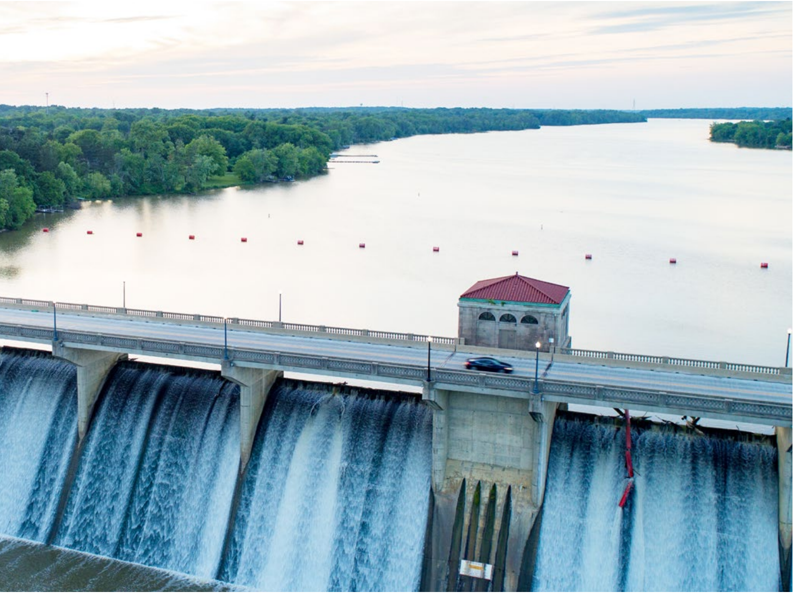
The stakeholder engagement presented an essential perspective on the status and needs of stakeholders in the dam industry in managing climate change impacts to dams in Canada. Opportunities for research and development include increasing climate data availability and the capability of stakeholders to access and interpret it properly. Most stakeholders who had begun addressing climate risk to dams had conducted climate risk assessments to determine where a dam system is potentially vulnerable to climate change. Few actual adaptation measures or projects were reported, other than projects focused on identifying the highest climate risks. Several stakeholders had not taken steps towards assessing climate vulnerabilities or adapting where needed. Some expressed a lack of clarity on the steps to take, others lacked incentive to act.

The inconsistency in the consideration of climate risk and the potential vulnerabilities identified for dams in Canada presents a need for guidance on the steps to take towards climate adaptation. Stakeholders were interested in having processes and best practices for climate change adaptation outlined, but there were also some identified barriers. These included limitations in the availability and interpretation of climate data and limited industry experience in applying this data to assess impacts and adaptation actions for a site or watershed. The following actions were provided as a road map towards climate adaptation to address current barriers and seize opportunities for industry alignment:

1. Assess and address climate change data needs for dams through research and collaboration.
2. Establish best practices and prepare a guidance document for conducting climate change vulnerability and risk assessments for dams.

3. Establish best practices for climate and non-climate related risk-based decision-making for dams.
4. Create a process that can be used to guide adaptation decision-making through consultation with stakeholders and researchers who have worked on climate adaptation specific to dams.
5. Conduct further research on the climate change related impacts to small dams and prepare a guidance document with climate adaptation considerations specific to small or lower consequence dams.

To address these opportunities, research and consultation would be needed to determine the appropriate level of detail to ensure the feasibility and robustness of guidance documents. This study concluded that climate adaptation best practices compiled in a standard or guideline would be valuable for Canadian dam owners and practitioners as it could provide knowledge of unknown risks and tools for appropriate adaptation to climate change.



"The impacts that climate change may have on dams and the need to act is not yet well understood, and the path forward to address climate changes to dams is even less clear."

1 Introduction

Canada is a geographically diverse nation rich in freshwater rivers and lakes, which have seen the construction of water dams for centuries. Both ageing and new water dams are impacted by the hydrological cycle and the environmental and climate conditions in the regions where they exist. Climate change is expected to bring weather that is hotter, wetter, and wilder, which could impact dams across the country. As Canada moves to adapt infrastructure to the effects of climate change, critical infrastructure owners must consider how climate change will impact their assets and operations.

In the Canadian dam industry, existing dam safety and operations guidelines and regulations do not specifically address how to adapt dams to climate change. Therefore, stakeholders are at varying points in the journey to adapt to the changing future climate conditions. Although high level guidance on climate adaptation and world-class dam safety guidelines exist, the combination of the two is lacking. The impacts that climate change may have on dams and the need to act is not yet well understood, and the path forward to address climate changes to dams is even less clear.

In that context, there is a need to better understand the climate risks impacting dams in Canada; the existing standards, guidelines, and best practices that address climate adaptation for dams; what is currently being done to address the issue; and what solutions are needed. This study reviews the relevant climate trends and vulnerabilities of dams in Canada, along with the related existing literature and documentation. It assesses the current state of adaptation to climate change in Canadian organizations including best practices, resources, and barriers to adapt. Ultimately, it seeks to identify opportunities for climate adaptation in Canada through various solutions such as standards, guidelines, tools, and research that can provide the most value to the dam industry.

Although this study focuses on water dams, many of the vulnerabilities and adaptation actions described will be applicable to mining dams as well. However, the literature, standards, and best practices will differ in the mining industry, and therefore the conclusions of this study would need to be adapted to the specifics of mining dams.

2 Methods

This study consisted primarily of a literature review, interviews, and a workshop with a representation of key stakeholders across Canada. The literature review and interviews informed the preliminary discussions and conclusions, which were then validated and expanded on in the workshop.

2.1 Literature Review

The literature review focused primarily on Canadian resources in French and English, and referred to some international literature. The review synthesized documents that either directly or indirectly addressed climate change impacts to dams in Canada. The objective was to understand the current landscape of climate adaptation for dams including vulnerabilities, existing adaptation strategies, best practices, and barriers to adaptation. The review did not exhaust the technical literature on climate and hydrological sciences, nor go into detail on all possible climate vulnerabilities, adaptation measures, and best practices being used across the world. Instead, vulnerabilities and adaptation measures most relevant to the Canadian context were discussed. Findings can be found in Sections 3 and 4, and are discussed in Section 5.

2.2 Stakeholder Interviews

The objective of the interviews was to gather knowledge from a diverse group of stakeholders in the dam industry regarding adaptation to climate change in design, operations, and regulations. The content of each interview differed based on the nature of the organization, but generalized interview questions were prepared (see Appendix A). Discussions explored the vulnerability of dams to climate change; if and how climate change is considered within the organization (e.g., policies, research, risk assessment, asset management methodologies, etc.); barriers to adaptation; key resources; and a discussion on the potential need for a Canadian guideline, tool, or standard.

Group interviews were conducted where stakeholders represented the same organization, association, or had similar interests and expertise but would address two different facets of the interview questions. Most interviews included between two to five participants, which allowed for a collaborative knowledge exchange. A total of 14 interviews were conducted with 35 stakeholders representing 16 organizations from public and private dam owners, regulators, utilities, scientists and researchers, and industry associations. Some representation gaps were identified in the interview phase. These gaps were to be filled during the workshop by including representatives from First Nations communities, Atlantic, and central provinces.

2.3 Workshop

Preliminary research findings from the literature review and stakeholder interviews were presented to a group of stakeholders, then validated and discussed in a workshop. There were 22 stakeholders in attendance, including many interviewees and some additional participants. Attendees could comment on preliminary findings in a large group discussion, and discuss selected topics in more detail in small groups. Geographical gaps in the research and interviews were also addressed by gaining input from representatives from those areas.

3 Literature Review

3.1 Jurisdictional and Regulatory Considerations

Dam construction, operation, maintenance, and decommissioning in Canada is provincially and territorially regulated [1]. There is no overarching federal regulatory agency or power to mandate the safe management of dams. Exceptions include dams built in navigable waters; located on the boundary with the USA (via the International Joint Commission) [2]; built and operated by the Canadian nuclear industry (via the Nuclear Safety Commission) [3]; as well as dams that may involve the Fisheries Act [4], Species at Risk Act [5], the Environmental Act [6], and the Nuclear Safety and Control Act [7].

Dams in Canada are owned by federal, provincial, and municipal governments as well as utilities, industrial and mining companies, irrigation districts, non-governmental organizations (NGOs), private companies, and individuals. Dams owned by the federal government are exempt from provincial regulations [7].

The provinces of Alberta, British Columbia, Ontario, and Québec have various degrees of custom regulatory requirements, while other jurisdictions rely on industry best practices as published by the Canadian Dam Association (CDA)[1] [7]. Most jurisdictions have some iteration of a water protection act that must be followed

1 The Canadian Dam Association (CDA) is a volunteer organization formed in the 1980s to provide dam owners, operators, consultants, suppliers and government agencies with a national forum to discuss issues of dam safety in Canada.

by dam owners and operators. Some dams may also fall between two jurisdictions if they or their systems cross provincial borders, in which case they may be subject to more than one set of regulations.

3.1.1 British Columbia

The dams in the province of British Columbia are regulated by the Dam Safety Regulation (2016) [8] under the Water Sustainability Act (2016) [9]. This regulation holds dam owners responsible for the safety of their dams and for any damage caused by their construction, operation, or failure. Owners must inspect their own dams, undertake proper maintenance, and ensure their dams meet ongoing engineering standards. The Dam Safety Program (established in 1967) [10], which includes the Dam Safety Audit Program policy, exists under this regulation. The policy requires that high, very high, and extreme consequence classification dams be evaluated for compliance with standards at least once every 5 years, and very significant (one tier below 'high') consequence classification dams be evaluated once every 10 years. Owners found not to comply with regulations are subject to enforcement action by the Ministry of Forests, Lands, Natural Resource Operations, and Rural Development (MFLNRO). Several non-prescriptive provincial guidelines have also been developed, including Engineers and Geoscientists British Columbia's[2] (EGBC) Legislated Dam Safety Reviews in B.C. [11] and Site Characterization for Dam Foundations [12].

Within the jurisdictional context of British Columbia there are few mentions of dams and climate change. The Water Sustainability Act contains one minor reference encouraging decision makers to take the effects of climate change into consideration during the thirty-year review of their licencing agreements. The bulk of information on climate change can be found in EGBC's guideline documents. The 2019 Professional Practice Guideline Site Characterization for Dam Foundations in BC V1.2 notes that climate change can be considered a key risk factor when undertaking site characterizations and provides recommendations on what climate considerations should be included in reporting.

The 2016 Legislated Dam Safety Reviews in BC-APEGBC Professional Practice Guidelines V3.0 mentions that dam safety reviews should consider the impacts of climate change on the safety status of the dam at the time of the review report. However, the guidelines also concede that the period of validity of the dam safety review report is very short in comparison to the timeline of climate change. The most comprehensive provincial-level guideline is the 2018 Legislated Flood Assessments in a Changing Climate in BC V2.1. It outlines a risk-based approach for incorporating climate change into dam design and operations [13].

3.1.2 Alberta

The dams in the province of Alberta are regulated by the Province of Alberta Water Act (2000) [14], The Alberta Dam and Canal Safety Directive (2018) [15], and the Water (Ministerial) Regulation (2020) [16]. The Water Act regulates the conservation and management of water, including allocation and use. The Dam and Canal Safety Directive is a non-prescriptive directive providing directions on the application and authorization of new dams, consequence classifications, safety management, investigation, design, construction, assessments, and evaluations, operation, maintenance and surveillance, emergency management, notifications to director, and decommissioning, closure, and abandonment. The Water (Ministerial) Regulation oversees water activities and uses in Alberta.

There is no specific mention of climate change with Alberta provincial guidelines or bulletins.

3.1.3 Ontario

The dams in the province of Ontario are regulated by the Ministry of Northern Development, Mines, Natural Resources & Forestry (DNMNRF) under the Lakes & Rivers Improvement Act (2019) [17]. The Act authorizes DNMNRF to regulate dam location, design, construction, decommissioning, operation, and maintenance. The DNMNRF has created a series of technical bulletins and best management practices

2 EGBC is the organization's business name, which changed in 2014. The legal name of the organization has remained Association of Professional Engineers and Geoscientists BC.

with mandatory requirements, technical guidance, and best practices [18].

There is no specific mention of climate change within Ontario provincial guidelines or bulletins.

3.1.4 Quebec

The dams in the province of Quebec are regulated under the Dam Safety Regulation [19] (established under the Dam Safety Act [20]), the Watercourses Act [21], the Environment Quality Act [22], and the Act respecting the conservation and development of wildlife [23]. The Dam Safety Act provides authority to the Ministère de l'Environnement et de la Lutte contre les changements climatiques (MELC) (Minister of the Environment and Fight Against Climate Change) to oversee the administration and regulation of the Act. The purpose of the Act is to increase the safety of the dams the Act applies to and protect people and property against the risks associated with dams by providing minimum requirements to dam owners. Under the Act, every high-capacity dam owner must periodically have their dams undergo a dam safety review by an engineer. Quebec also differs from other provinces in that the level of consequence of dams is mainly based on the affected infrastructure including residential buildings as opposed to the potential for loss of life in a dam break.

There is no specific mention of climate change within Quebec provincial Acts or regulations related to dams.

3.1.5 Other Provinces and Territories

All other provinces and territories lack distinct and separate regulation or legislation for dams. Any regulation regarding dams falls instead under the provincial water or environmental act. This includes Saskatchewan's Water Security Agency Act (2020) [24], Manitoba Water Right's Act (2021) [25], New Brunswick's Clean Water Act (1989) [26], Nova Scotia's Environment Act-Regulation (1994) [27], Newfoundland and Labrador's Water Resources Act (2002) [28], Prince Edward Island's Water Act (2021) [29], Yukon's Waters Act (2003) [30], Nunavut's Nunavut Water & Surface Rights Tribunal Act (2002) [31], and Northwest Territories' Mackenzie Valley Resource Management Act (1998) [32] and Waters Act- Justice (2014) [33]. If no formal provincial requirements exist, it is industry standard to follow the CDA guidelines [34].

There is no specific mention of climate change within these provincial or CDA guidelines.

3.1.6 Canada's Nuclear Industry

Dams related to Canada's nuclear industry are regulated by the Canadian Nuclear Safety Commission (CNSC) under the Nuclear Safety and Control Act (2000) [35]. Dams at Canada's nuclear facilities and sites are regulated through the CNSC's licencing and compliance activities. This CNSC oversight is based on a risk-informed approach and conducted to obtain assurance that the dams are designed appropriately and maintained with adequate provision for dam safety and for protection of the health and safety of persons and the environment. Any dams on nuclear sites will be reviewed by CNSC staff and in-house experts before being approved.

There is no specific mention of climate change within CNSC documents.

3.2 National and Federal guidelines

There are no existing national guidelines on climate change adaptation and dams in Canada. The most widely used guideline document is CDA's Dam Safety Guidelines, published in 2007 and updated in 2013. The guidelines have become an important reference document for dam safety in Canada and consist of principles applicable to all dams, and an outline of processes and criteria for management of dam safety according to the principles. The CDA guidelines are supported by a set of nine technical documents published in 2007 and revised as needed [7].

Federally, except for the Acts lists in Section 3.1.1, there is only one overarching guideline developed by Parks Canada for the dams under their purview. The Directive for Dam Safety of Parks Canada Dams and Water-Retaining Structures document was created as management guide for Parks Canada dams and water-retaining structures throughout their life cycle. These guidelines provide consistent, national guidelines for designing, constructing, inspecting, and maintening the dams [36]. This guidance does not consider climate change.

3.3 International Standards

No specific international standards that consider the impacts of climate change and dams were identified. The ISO (International Organization for Standardization) has developed several guidelines that may be relevant, including:

- *ISO 24516-2:2019 Guidelines for the management of assets of water supply and wastewater systems — Part 2: Waterworks,* which includes consideration of reservoirs but does not consider climate change,
- *ISO 31000 Risk Management,* which is a common risk assessment guideline that does not specifically consider climate change; however, it is referenced by Infrastructure Canada's Climate Lens as a suitable methodology for conducting climate change resilience assessments,
- *ISO 14090, Adaptation to climate change – Principles, requirements and guidelines,* which does not mention dams but is focused on the basics of climate change adaptation, and
- *ISO 14091:2021 Adaptation to climate change — Guidelines on vulnerability,* impacts and risk assessment, which does not mention dams but is focused on the basics of climate vulnerability, impact, and risk assessments.

ICOLD has several bulletins on dam safety, notably Bulletin 59 on Dam Safety Guidelines (1987), Bulletin 167 on *Regulation of Dam Safety: An overview of the current practice worldwide* and bulletin 189 on *Current State-Of-Practice in Risk-Informed Decision-Making for The Safety of Dams and Levees.* Other bulletins address climate change like ICOLD's Bulletin 169 on *Global Climate Change, Dams, Reservoirs and related Water Resources*, discussed further in Section 3.5.1.

3.4 Vulnerability of Dams to Climate Change

3.4.1 Exposure, Climate Hazards, and Trends

Current and projected conditions and trends in climate are highly geographically and temporally dependent. As a product of its size and diverse landscapes, Canada's climate is wide ranging and naturally fluctuates from one year to another, and one decade to another. The following section aims to give an overview of the national projected trends in climate, but those conditions may vary in individual locations. The climate parameters listed below were chosen based on the literature review and discussions with experts in the industry for their potential impacts to dams.

Natural variability in climate systems is an important factor that must be considered when discussing climate change and the potential impacts on dams. Natural climate variability refers to the short-term fluctuations around the mean climate at a location or over a region. Some natural variability can take place on larger temporal or geographical scales, such as the El Niño-Southern Oscillation (ENSO), which brings warmer air temperatures and drier conditions across much of the country [37]. Climate change is a slower long-term backdrop to those shorter natural fluctuations and can shift the mean and natural variability.

The following section will discuss both the historical observations of climate change as well as future projections. Climate projections are partially dependent on historical records of climate. While much of the southern portion of the country has consistent records dating to the 1900s, the northern regions and Canada as a whole is limited to a period starting in 1948 [37]. Similarly, observation sites are often densely distributed around urban and southern areas and are far sparser in the northern regions. Meanwhile, many dams, especially with larger structures, are located in northern or remote regions.

Climate models use inputs known as 'emissions scenarios' when determining future climate projections. Emissions scenarios are images of how the future might unfold based on driving forces such as demographic development, socio-economic development, and technological change, and their impact on greenhouse gas concentrations in the atmosphere. A low emission scenario assumes rapid and deep emissions reductions and near-zero emissions in this century, while a high emissions scenario assumes continued growth in emissions in this century. In total, there are four commonly used emissions scenarios developed to fit different possible narratives of the future, known as 'Representative Concentration Pathways' or 'RCPs' [37]. This review has, where possible, used projection data from a high emissions scenario (RCP 8.5) to remain conservative

Table 1: Observed changes in annual and season mean temperature between 1948 and 2016 for six regions and for Canada

Region	Changes in Temperature °C				
	Annual	Winter	Spring	Summer	Autumn
British Columbia	1.9	3.7	1.9	1.4	0.7
Prairie	1.9	3.1	2.0	1.8	1.1
Ontario	1.3	2.0	1.5	1.1	1.0
Quebec	1.1	1.4	0.7	1.5	1.5
Atlantic	0.7	0.5	0.8	1.3	1.1
Northern Canada	2.3	4.3	2.0	1.6	2.6
Canada	1.7	3.3	1.7	1.5	1.7

when considering potential impacts. It has been noted when another scenario was used due to lack of data. The expected changes to climate parameters and hazards are presented below to provide an understanding of Canada's exposure to climate change. The vulnerability of dams to climate change is discussed in further sections. Risk is the combination of exposure and vulnerability, therefore these sections provide a discussion on potential climate risk to dams in Canada.

3.4.1.1 Temperature

There are high levels of certainty in the models showing that annual and seasonal mean temperatures across Canada have already increased. Between 1948 and 2016, the best estimate of mean annual temperature increase was 1.7 °C for the country as a whole [38]. Increases in winter temperatures have been most prominent in Northern British Columbia and Alberta, Yukon, Northwest Territories, and western Nunavut ranging from 4 °C to 6 °C for the same time period [39]. Spring has followed a similar pattern across the country, but with smaller magnitudes. Summer warming has been of a much smaller magnitude than winter or spring but has generally been more uniform across the country as compared to the other seasons. During autumn, most increases have been observed in the northeastern regions of the county, mainly in northern Northwest Territories, Nunavut, and northern Quebec [39]. Table 1 highlights the observed regional changes in annual and seasonal mean temperatures across the country between 1948 and 2016 [39].

Both observed and projected mean increases in Canada are thought to be about twice the global mean rate, regardless of emissions scenario. Averaged over the county, warming projected in a high emissions scenario (RCP 8.5) is about 6 °C higher than a 1986-2005 historic baseline by the late 21st century [39]. Projected increases in temperatures are most evident at higher latitudes, and in the winter and annual mean. In southern Canada, projected winter temperature change is greater in the east than in the west, and British Columbia is projected to warm slightly less than elsewhere in the country [39]. Table 2 highlights the projected change in annual mean surface temperature for regions across the country [39]. The information includes the 25th and 75th percentiles of the modelled data as per the RCP 8.5 emissions scenario.

Table 2: Projected change (in °C) of annual mean surface air temperature as per RCP 8.5 for six regions and all Canadian land area, relative to 1986-2005 (with 25th and 75th percentiles)

Region	Time horizon	
	2031-2050	2081-2100
British Columbia	1.9 (1.4, 2.5)	5.2 (4.3, 6.2)
Prairies	2.3 (1.7, 3.0)	6.5 (5.2, 7.0)
Ontario	2.3 (1.7, 2.9)	6.3 (5.3, 6.9)
Quebec	2.3 (1.7, 2.9)	6.3 (5.3, 6.9)
Atlantic	1.9 (1.5, 2.4)	5.2 (4.5, 6.1)
North	2.7 (2.0, 3.5)	7.8 (6.2, 8.4)
Canada	2.3 (1.7, 2.9)	6.3 (5.6, 7.7)

It is important to note that year-to-year internal variability of the climate will continue to occur in tandem with a slowly changing climate. The future will continue to have extreme warm and cold periods on the backdrop of a gradual forced shift in climate.

3.4.1.2 Precipitation

Observed precipitation across Canada has increased by approximately 20% from 1948 to 2012 [38]. Those increases were larger in Northern Canada, including Yukon, Northwest Territories, Nunavut, and Northern Quebec, than in southern Canada [39]. Significant increases were also observed in eastern Manitoba, western and southern Ontario, and Atlantic Canada.

There is only medium confidence that annual mean precipitation has increased in the country, and a low confidence in the estimate of the magnitude of the national trend due to the insufficient station density in the country. In northern Canada, precipitation has increased in every season. In southern Canada, precipitation has increased in most seasons, but that increase is generally not statistically significant, with the exception of British Columbia, Alberta, and Saskatchewan, which have seen statistically significant decreases in winter precipitation. Table 3 highlights the observed changes in annual and seasonal precipitation between 1948 and 2012 for regions across the country [39].

In terms of short-duration extreme precipitation events in Canada, for the country as a whole, there do not appear to be detectable trends. More stations have experienced an increase rather than a decrease in the highest amount of one-day rainfall each year, but the direction of the trends is random over space and not more than what would be expected from chance [40] [41, 42]. This is inconsistent with global trends and those from the contiguous regions of the United States.

The number of heavy rainfall days has increased by only 2 to 3 days since 1948 in southern British Columbia, Ontario, Quebec, and the Atlantic provinces [43]. The number of days with one-hour total rainfall greater than 10 mm, with 24-hour total rainfall greater than 25 mm, or with 48-hour total rainfall greater than 50 mm also did not show any consistent change across the country [41].

Detected changes attributable to human activities in historical precipitation trends are less significant when compared to temperature trends. This distinction is mainly due to greater spatial and temporal variability in precipitation data, rather than to a smaller amplitude of change. The expected changes in precipitation in response to increasing temperatures may be small when compared to natural variability. In addition, on a regional scale (as compared to global), limited long-term observations may make detection more difficult [39].

Table 3: Observed changes in normalized annual and seasonal precipitation between 1948 and 2012 for six regions and all Canadian land area

Region	Changes in Precipitation Between 1948 and 2012 (%)				
	Annual	Winter	Spring	Summer	Autumn
British Columbia	5.0	-9.0	18.2	7.9	11.5
Prairie	7.0	-5.9	13.6	8.4	5.8
Ontario	9.7	5.2	12.5	8.6	17.8
Quebec	10.5	5.3	20.9	6.6	20.0
Atlantic	11.3	5.1	5.7	11.2	18.2
Northern Canada	32.5	54.0	42.2	18.1	32.1
Canada	18.3	20.1	25.3	12.7	19.0

In general, precipitation projections are considered less certain and more difficult to accurately model than temperature. There is only a medium confidence that a human-caused contribution exists in observed global-scale precipitation changes over land since 1950. However, looking at climate projections for future precipitation shows that changes should be expected. Annual and winter precipitation are projected to increase across the entire country over the course of the 21st century, with larger percentage changes anticipated in northern Canada. Summer precipitation is projected to decrease over southern Ontario. Daily extreme precipitation is projected to increase. Table 4 highlights the projected changes in annual mean precipitation for regions across the country relative to a 1986-2005 historic baseline [39]. The table also includes the 25th and 75th percentiles of the modelled data as per the RCP 8.5 emissions scenario.

Table 4: Projected percentage change (%) in annual mean precipitation as per RCP 8.5 for six regions and for all Canadian land area relative to 1986-2005 (with 25th and 75th percentiles)

Region	Time horizon	
	2031-2050	2081-2100
British Columbia	5.7 (0.0, 11.4)	13.8 (5.7, 22.4)
Prairies	6.5 (0.4, 13.1)	15.3 (6.3, 24.9)
Ontario	6.6 (1.8, 12.4)	17.3 (8.5, 26.1)
Quebec	9.4 (4.5, 14.7)	22.5 (14.8, 32.0)
Atlantic	5.0 (0.6, 9.9)	12.0 (5.7, 19.3)
North	11.3 (5.4, 18.1)	33.3 (22.1, 46.4)
Canada	7.3 (2.0, 13.2)	24.2 (13.7, 36.2)

In the near-term (2031-2050), a small (less than 10%) increase is projected for all seasons, with slightly larger values projected for the northeast. In the long-term (2081-2100), projected changes are much larger, with extensive areas of increased precipitation in northern Canada anticipated. Annual and winter precipitation is projected to increase everywhere in Canada over the course of the 21st century, with larger percentage changes in the northern regions. Summer precipitation is projected to decrease in southern Canada under a high emissions scenario (though only low increases are projected under a low emissions scenario) [39].

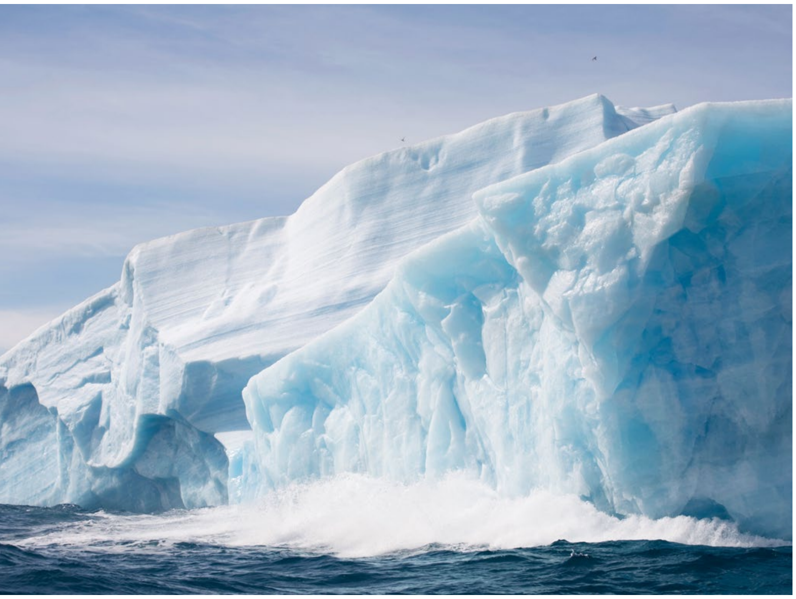
There is a lack of observational evidence of changes in sub-daily extreme precipitation amounts for the Country as a whole. In the future however, there is a high confidence that daily extreme precipitation amounts will increase. Extreme precipitation is projected to increase across the country. Extreme precipitation with a return period of 20 years is projected to become a 10-year event in the near term (2031-2050), and a 5-year event in the long-term (2081-2100). This relative change in frequency is larger for more extreme and rarer events [39]. Since dams are designed for much larger return period events (1,000 to 100,000 years for example), this could be a concern. The impact of changes to precipitation on design floods for dams has been studied by Ouranos and is discussed further in Section 3.5.6.

It should be noted that it is difficult to interpret the results from global climate models at a local scale, especially for precipitation. The results from these models may convey information in an impractical way for operational use at a local scale and may not include all physical processes that produce local intense precipitation events [39].

3.4.1.3 Snow Accumulation and Snow cover

Historical observations have shown that the seasonal snow accumulation and the portion of the year with snow cover have decreased across most of Canada. Since 1981, the snow cover fraction (the portion of days each month that snow is present on the ground) has decreased between 5-10% per decade due to late onset and earlier spring melt [44]. This is especially notable for eastern Canada in spring, and most of the country in the fall. In the same period seasonal snow accumulation has also decreased by 5-10 % per decade, except for southern Saskatchewan, and parts of Alberta and British Columbia, which have seen increases of 2-5 % per decade [44].

During the winter months there are projected decreases in snow across southern Canada, where temperature increases will result in less snowfall as a proportion of total precipitation [45]. Temperatures in the northern regions are projected to remain sufficiently cold in the winter to not see changes in snow cover in response to warming. During spring, however, regions of projected



"Glaciers and alpine ice caps in Canada have thinned over the past five decades due to increasing surface temperatures."

reduction in snow melt are expected to shift north, as snow cover retreats across the boreal forest, sub-Arctic, and high Arctic [44].

Projections indicate that reductions in the maximum snow water equivalent (amount of water in the form of snow) will be extensive (15% to 30% from 2020-2050) for much of southern Canada, with the greatest changes occurring in the Maritimes and British Columbia. The greatest snow loss across the country is projected to occur in the shoulder seasons (October to November and May to June) [44].

3.4.1.4 Glacier and Ice Cap Melt

Glaciers and alpine ice caps in Canada have thinned over the past five decades due to increasing surface temperatures. The health of these systems is often measured by surface mass balance, the difference between annual mass gained through snow accumulation, and mass lost due to snow melt [44].

Reduction in surface mass balance has already been observed throughout southern Canada. Increasing temperatures and periods of reduced precipitation in western Canada have caused a thinning of the glaciers in the southern Cordillera by 30 to 50 m since the early 1980s [46]. Similar trends have been seen across the country, including reductions observed in the glaciers of Garibaldi Provincial park, the Canadian Rocky Mountains, the Columbia Icefield, Cariboo Mountains in the west, and in the Torngat mountains in the east [47] [48] [49] [50].

Glaciers and ice fields in the northern regions have also seen measurable reductions. In the Yukon, these have decreased by approximately 22% between 1957 and 2007 [51]. The Canadian Arctic Archipelago has seen the amount of reduction in its mass more than double from 1995-2000 and from 2003-2010 as per two studies on those time periods. The reduction has continued to accelerate [52]. The Barnes Ice Cap on Baffin Island has lost 17% of its mass from 1900-2010 [53].

Most small ice caps and ice shelves in the Canadian Arctic will disappear by 2100 [44]. Larger ice caps in that region will lose 18% of their total mass by the end of the century [54] [55]. Glaciers across the Western Cordillera are projected to lose up to 85% of their volume by the end of the century [44]. Rivers fed by those glaciers may initially experience increased discharge periods due to greater meltwater supply, but this is expected to be finite and lead to a reduction in summer streamflow by the middle of the century (2050). These changes will have significant impacts to dam owners with infrastructure on glacier-fed rivers, and communities depending on glaciers for water supply. There is also a risk that glacier melt can lead to ponded water breaching a natural glacier dam, causing flash flooding downstream and risk of cascading dam failures.

3.4.1.5 Changes to Lake and River Ice

The duration of seasonal lake ice cover has declined across Canada over the past five decades due to later ice formation in the autumn and earlier spring breakup.

Surface observations have shown that ice breakup is occurring earlier, and freeze onset is later across small lakes in southern Quebec, Ontario, Manitoba, and Saskatchewan [44].

There has been no significant trend observed in the seasonal maximum lake ice cover for the Great Lakes, which has been highly variable since 1971 [44]. A significant declining trend in annual maximum ice cover was observed from 1973-2010 (71% decline for all the Great Lakes), but heavy ice years in 2014, 2015, and 2018 resulted in no trend over the 1973-2018 period [56]. Satellite measurements show that lakes in Arctic Canada have been experiencing earlier dates when the water is clear of ice, and a decline in ice cover duration in 80% of Arctic lakes from 2002 to 2015 [57].

There is a lack of assessment of the change in river ice across the country due to sparse observations and analysis of the available data [44]. There is evidence of earlier river-ice breakup consistent with increases in surface temperature. However, the relationships between climate and ice phenology and thickness, changing seasonal flow regimes, hydraulic processes, and ice jams and flood events is not fully understood [58] [59].

Projections indicate that spring lake ice breakup will occur 10 to 25 days earlier by the middle of the century and fall freeze-up may occur 5 to 15 days later (varying by emissions scenario and lake-specific characterizations) [60] [61]. More extreme reductions of up to 60 days are projected in coastal regions [44]. Increasing temperatures are projected to result in earlier river ice breakup in spring due to decreased mechanical ice strength and earlier onsets of peak discharge. More frequent mid-winter breakup and associated ice jam events are anticipated, although projected changes in river ice properties may reduce ice obstructions during the passage of the spring freshet [62].

3.4.1.6 Melting Permafrost

Permafrost underlies about 40% of the landmass in Canada and is an important consideration for structural stability in northern regions [44]. There is a very high confidence that permafrost temperatures have increased over the past 3 to 4 decades, with regional observations identifying warming rates of about 0.1 °C per decade in the central Mackenzie Valley and 0.3 °C to 0.5 °C per decade in the high Arctic [63]. Active layer thickness (the top layer of soil that thaws during the summer and freezes during the autumn) has decreased approximately 10% since 2000 in the Mackenzie Valley. Note that permafrost conditions are challenging to monitor because they require in situ monitoring in areas difficult to access [44].

In northern Quebec, permafrost continues to warm at rates between 0.5 °C and 1 °C per decade [64] [65]. In the past five decades, there has been a noted loss of permafrost mounds, collapses of lithalsas, and increased sizes of thermokarst ponds in the region, providing additional evidence of changing permafrost conditions [66] [67]. Additional evidence of permafrost loss has been found in the Mackenzie mountains of the Northwest Territories, along the Alaska Highway corridor (between Whitehorse and St. John), in the Old Crow Flats (Yukon), and in the Southern Northwest Territories [68] [69] [70] [71].

There are uncertainties regarding quantitative projections of future changes in permafrost due to the inadequate representation of soil properties and uncertainty in understanding the response of deep permafrost, as well as the intersection of precipitation events, vegetation growth, wildfires, and human activities [44]. Simulations from models considering deeper permafrost and driven by low and medium emissions scenarios project that the area underlain by permafrost in Canada will decline by approximately 16% to 20% by 2090 relative to a 1990 baseline [72].

3.4.1.7 Wildfire

Projected changes in the frequency of temperature and precipitation extremes and regimes can lead to an expected change in the likelihood of wildfire events. The Canadian Forest Fire Weather Index (FWI) is a collection of weather variables used to characterize fire risk. A threshold of this index is often used to define days conducive to fire spread [73] [74]. Large year-to-year variability in the FWI has hindered historical detection of trends across the country [75] [76]. A study found that the mean number of fire spread days across Canada increased from 1972 to 2002, although trends were regional and not all were significant [73]. Despite inconsistencies in the indices, there has also been significant increase in the areas that burned annually across Canada [77] [78].

Projected increases in temperature will likely contribute to increased values of the FWI indices, and therefore lead to an increased fire risk. Increases in fire spread days and extreme values of the FWI are projected as well as an increase in the length of the fire season in Canada [39].

3.4.2 Dam Vulnerabilities

Climate trends and hazards identified in the previous section can impact the design of new dams, alter operations, or pose a threat to existing dams. The following sections discuss these potential vulnerabilities.

3.4.2.1 Design

3.4.2.1.1 Inflow Design Flood

According to the CDA guidelines, dams are required to withstand an Inflow Design Flood (IDF) with a magnitude determined based on their classification [7]. The classification of dams is done according to the consequences level of a dam failure, including loss of life, injury, property and environmental damage in the inundated area. Classification levels and associated Inflow Design Flood (IDF) criteria are presented in Table 5 with the suggested revision frequency of the Dam Safety Reviews (DSRs). It is also recommended that DSRs or appropriate investigation be performed when extreme hydrological events occur, as it may have an impact on the magnitude of the IDF and a dam's ability to withstand and discharge it.

The impact that climate change may have on the design flood is hard to quantify and depends on a myriad of parameters including the location and size of the watershed [79]. The process of using climate projections to estimate floods has multiple layers of uncertainty [80]. According to Ouranos, it will be up to engineers performing designs and Dam Safety Reviews to assess the site-specific impact on IDF caused by climate trends and to demonstrate a dam's resilience to climate change [80].

Table 5 shows that for Low hazard dams, DSRs and IDF values do not require regular review. However, based on climate change projection data, 1 in 100 return period events are expected to occur more frequently. While the actual occurrences of these events increase, the statistical probabilities of those events should also be revised to consider climate change. It is possible that the dams currently designed for the 1 in 100-year event would need to revise their IDF and potentially make changes to the flood capacity of the dam.

3.4.2.1.2 Storage and Spill Capacity

While extreme hydrological events may require greater reservoir storage or spillway capacity to be managed, climate change may add stress to the situation.

Table 5: Periods of recurrence of Inflow Design Flood (IDF) and Dam Safety Review update recommendations from the CDA *Dam Safety Guidelines* [7]

Classification of dams based on the level of consequence	IDF recommendations - Annual exceedance probability of a flood	Suggested frequency of dam safety reviews
Low	1/100	Not required
Significant	1/100 to 1/1000	10 years
High	1/3 between 1/1000 and PMF[1]	7 years
Very high	2/3 between 1/1000 and PMF[1]	5 years
Extreme	PMF[1]	5 years

[1] Probable maximum flood

Debris-flow events are expected to be more frequent and intense in mountainous regions in the future [81] and have been identified as a risk in the climate change context for dams [82]. In ICOLD Bulletin 170 on Flood Evaluation and Dam Safety, a scenario with debris blockage of 25% of gated spillways evacuation capacity in forested area needs to be considered for the spill capacity of the IDF [83].

Frazil ice can clog water intakes and turbines, or accumulate and cause ice jams, as identified by Ouranos [84], although the impact of climate change on its production is hard to quantify at this point. It is believed that the delayed formation or absence of an ice cover on some rivers may increase frazil ice production [85]. An example in the literature showed that in Quebec, a public dam owner saw an increase in high floods in late November and early December that caused serious frazil ice problems for their assets [86]. Response and mitigations were not discussed for frazil ice impacts to dams due to climate change.

Increased precipitation as rain and glacier melt can lead to increased runoffs and sedimentation in dam reservoirs [84] [87] [88] [89]. Sedimentation can lead to a very slow and subtle decrease of reservoir capacity that becomes significant over a period of years [82].

3.4.2.1.3 Hydraulic Modelling Boundary Conditions

A brief mention in the ICOLD Bulletin 170 on floods and dam safety suggests that sea level rise may need to be considered in dam breach or flood mapping hydraulic models for estuaries or locations where the sea level dictates water levels [83], but this may not be the case for many Canadian installations.

3.4.2.2 Operations

3.4.2.2.1 Shared Usage of Water Supplies

Shared usage of the water resource is a growing concern with climate change, as was demonstrated on the Mekong River Basin [90]. The impact of climate change on the frequency and intensity of flood and droughts, combined with the development of hydropower in China has led to serious repercussions on the agricultural and fisheries production. The changes in land use (i.e., urbanization) and flooding impact runoff, dam operations and sedimentation. The stresses on shared use of water supplies were also addressed by federal agencies in the United States, namely in the Climate Change and Water Resources Management document produced in 2009 [91].

In Canada, water resources are used for various functions: bottling, water supply for industry, municipalities, pisciculture, agriculture, and mining; as well as on site usage for hydroelectricity production, water transportation, fishing, sewage disposal and recreational activities [92]. The potential decrease in water quality and availability, the increased need for hydroelectricity to reduce carbon emissions, the increase in water demand for irrigation in dry periods, as well as population growth will increase the demand of all water resource uses, potentially leading to conflict.

3.4.2.2.2 Access

Access roads have been identified as a potential vulnerability of dams in a climate change context by the International Hydropower Association (IHA) in their Climate Resilience Guide [93]. Access roads are crucial to supporting safety and operations for dams [7], especially if they cannot be remotely operated. Potential risks include extreme hydrological events damaging the surface, permafrost melting, increased debris, and runoffs [93]. Ice roads can also form later, or ice cover can be too thin to be used for travel [93].

3.4.2.2.3 Cold Weather Operations

The operation of gate equipment can be inhibited by cold and ice [7]. The requirement to operate this equipment is predicted to increase with increased winter high flow events. Spray and icing was one of the circumstances surrounding the Spencer dam break in Nebraska, USA in 2019, which resulted in an inability for operators to remove stop logs from the gates [94]. This issue was also observed in Canada, in the spillway installation of Sainte-Marguerite-2 (SM-2) [95].

3.4.2.2.4 Power Outage and Control Systems

Extreme events like ice storms, hurricanes, high winds, and tornados could increase [37], damaging monitoring equipment, operating controls, and interrupting the power supply to critical equipment [96]. These events therefore represent risks to dams' operation and safety.

3.4.2.2.5 Hydropower Generation

While the highlighted climate trends will impact hydroelectricity production, the magnitude and type of impact differ based on the time horizon and region.

Landsvirkjun, The National Power Company of Iceland, has adapted the design and management of dams to reflect the increased flow due to glaciers melting, which has increased hydro-electricity production, for now [97]. The glacier melting rate is predicted to plateau in 2030 and remain constant until 2080. After 2080, the reduced glacier volume will cause a reduction in flows. Several Canadian dams are located on watersheds influenced by glaciers, including some in British Columbia, Alberta, Saskatchewan, Manitoba, and the Yukon [98].

International research on the effect of climate change on hydropower production has been conducted. A study [98] compared the type of dam, the reservoir size, and the area to volume ratio of the reservoir to four climate trends: evaporation, discharge, temporal variability, and glacier melt. Results showed that pumped storage hydro was only vulnerable to evaporation, while dams with reservoirs were vulnerable to changes in evaporation, discharge and glacier melt, but were somewhat resilient to temporal variability (floods, droughts, and seasonal offset). Run-of-river dams, on the other hand were mostly found to be vulnerable to temporal variability. Dams with storage that have a high area to volume ratio were more sensitive to evaporations than dams with smaller ratios.

Some studies were more specific to Canada. Precipitation trends and the impact on discharge varies locally, even within a watershed, as was shown for the Peribonka watershed [99]. This study evaluated discharge on four different sub basins based on climate projections for three different periods and compared it to historical data. Results show that while there is a general trend for earlier freshet, flows decrease in the summer-early fall and increase in the winter. The two southern sub basins had earlier and lower freshets than the two northern ones but greater winter flow increase. Spring high flows were projected to peak lower in the 2010-2069 horizon than was the case in the 1961-1990 period, but higher in the 2070-2099 period (except for one of the two southern sub basins). It was shown that using the current operating procedures, power production was expected to decrease due to climate change. By adapting operations, results show that the annual power production is expected to decrease until 2030 (due to decreased runoff in southern sub basin) and increase until 2099 (horizon limit for this study; due to greater spring floods). Overall, more inter-annual variability is to be expected.

In 2020, Ouranos presented a guide on evaluating hydropower assets in a context of climate change [100]. Some of the monetary vulnerabilities identified specific to hydropower include changes in demand; energy generation and power output; loss of active storage caused by a change in flood prevention measures; and an increase in insurance rates due to the increased frequency and magnitude of extreme events.

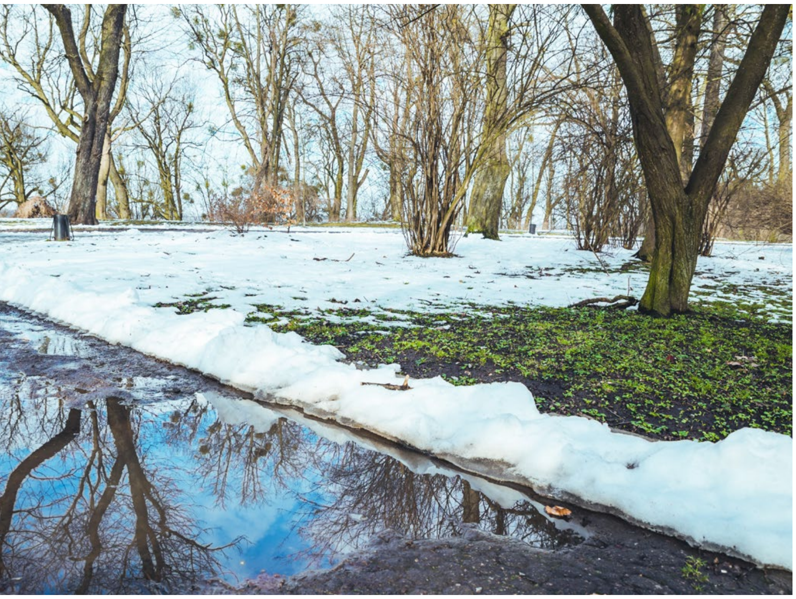
3.4.2.3 Dam Safety and Maintenance

3.4.2.3.1 Extreme Hydrological Events (Floods)

Turcotte et al. describe the major open-water floods of recent years in Canada (southern Quebec in 2011, Calgary and Toronto in 2013, western Quebec in 2017 and in 2019, as well as southern New Brunswick in 2018 and 2019) as events that could be caused by climate change, or at least that reflect what the Canadian floods future may look like [87].

Internationally, climate change was discussed in the ICOLD Bulletin 170 on Flood evaluation and dam safety [83]. The main expected impact of climate change mentioned in the Bulletin is an increase in uncertainty associated with extreme flood estimations.

A major dam safety concern for Canadian water dams is their ability to handle extreme flooding. The forecasted increase in extreme storm magnitude and frequency in several Canadian regions could render some dams more vulnerable to breaches, [101] although this depends on many factors. Intense floods can lead to overtopping and embankment failures, as well as structural damages [7] [101]. Extreme floods are particularly a concern for aging and deteriorating dams, as was proven on multiple occasions in the United States, including the 2020 breach of the Edenville Dam, which was deemed to be in unsatisfactory condition [102] [103] [104]. According to a study on two Toronto dams, while dams can be resilient to changes in



"Climate trends for most Canadian cities are evolving towards warmer winters and an increased possibility of winter thaws and precipitation as rain."

high flows, an increase in frequency or magnitude of extremely high flows caused by hurricanes or sustained thunderstorm could have major impacts on dams and should be reconsidered when appropriate scientific and political guidance is available [96].

The guidelines for flood mapping in British Columbia include the impact of climate change to be considered when performing flood mapping studies for dams. These are:

- Increased peak discharge for a given annual exceedance probability caused by extreme hydrological events and rate of snowmelt;
- An increase in forest fires and insect infestation phenomena that alters the landscape and leads to greater frequency and magnitude floods; and
- A combination of sea-level rise and higher storm surges that increase flooding and erosion in low-lying coastal areas [105].

3.4.2.3.2 Winter and Ice Considerations

Climate trends for most Canadian cities are evolving towards warmer winters and an increased possibility of winter thaws and precipitation as rain [106] [39]. These weather patterns could lead to increased winter seasonal high flows that can cause mid-winter dynamic break-ups in locations where the ice cover will remain thick and resistant (either northern locations, or for a shorter time horizon) [106]. Several sites prone to mid-winter dynamic break-ups that can lead to ice jams and floods with a high level of consequences may see more of these events occur. Recent examples of ice-induced winter floods include two Quebec City rivers on December 25th, 2020, and the four Quebec City rivers in mid-January 2018. Both events were extremely costly in damage repair [107].

Turcotte et al. highlight the lack of knowledge on ice-jams and winter floods as part of their research on the impact of climate change on ice-induced floods [87]. Based on their findings, there is a great regional variability on ice processes, depending on the climate trends governing the area (e.g. elevation, latitude, longitude). It appears that site-specific statistical analysis of historical water-level trends in the presence of ice and ice-hydrodynamic models [85] are among the most accurate methods of understanding the local impact of climate change, and the impacts on winter operations.

The Spencer dam failure in 2019 showed that dynamic ice break-ups, ice jams, and ice runs are direct concerns for dam safety. The report published by the Association of State Dam Safety Officials (ASDSO) indicates that the weather circumstances surrounding the ice run that led to the dam failure were a cold winter (thick ice and snow cover) followed by a winter storm with temperatures above freezing and precipitation (flood and dynamic ice-breakup) [94]. The flood wave caused several ice jams to burst upstream of the dam. Ice floes obstructed the opened gates and spillway, causing the water level in the reservoir to rise to the dike (i.e. embankment) crest. Overflow of the water and ice caused erosion on the downstream face of the dam, which led to the breach [94]. Some of the factors that led to these consequences were the small size of reservoir, insufficient evacuation capacity, and the upstream restrictions of the river by two bridges [94]. Of the 380 dam failures recorded in the ASDSO database, this was the second event attributed to ice dynamics [94].

Although few historical dam failures are related to ice runs in the United States, the colder climate of the Canadian provinces makes ice jams more common and these events could increase in the presence of climate change. Morse and Turcotte attempted to review the winter 2040-2070 climate trends for Canada and determine the effect on ice jams [108] [106]. The general observations made from the literature and from climate models suggested that the temperature rise is predicted to shorten the winter period for rivers (between ice cover formation and spring breakup), and ice thickness. However, Canadian rivers will not all be subjected to the same air temperature rise. In regions where temperatures remain cold enough to produce an ice cover, winter dynamic break-ups could become increasingly frequent and intense due to increased temperature and precipitation variability. This is also the case for Atlantic provinces and boreal areas. The regional tendencies for Quebec found in this report are a decrease in ice-related floods in the southern watershed of Quebec (lack of ice), an increased in winter floods (and dynamic break-ups) compensated by a shorter winter and thinner ice covers in middle regions, and an increase in frequency and intensity of winter floods (and ice-related flooding) in northern regions.

3.4.2.3.3 Coastal Erosion

While sea level rise and its impact on coastal erosion has not come up as a major concern for the safety and maintenance of dams in the literature available [98] [82], it was mentioned in that coastal infrastructure, presumably including dams, could be exposed to increased shoreline erosion [92].

3.4.2.3.4 Stability of Northern-region Dams

Permafrost thawing is a known impact of climate change that affects northern regions [109]. The impact of permafrost thaw on dams' stability was recognised but not addressed in the ICOLD Bulletin 169 on climate change [82] and is mentioned in CDA guidelines [110]. It seems that while this issue was addressed in codes and standards of other types of infrastructures (e.g. Standard CAN/BNQ 2501-500 *Geotechnical Site Investigation for Building Foundations in Permafrost Zones* [111]), there is limited literature specific for dams. Specific risk mitigation actions to reduce the risk or damages from permafrost thaw to dams were not identified.

3.4.2.3.5 Structural Integrity

Although most dams are robust and structurally can manage an increase in the magnitude or frequency of extreme events below their design thresholds [112] [96], the structural integrity of dams could be compromised by a change in extreme hydrological loads, debris impact [82], ice jam thrusts, or wave events. The potential changes in design loading are not significantly discussed in the literature. The reservoir levels of operation and resulting stresses on the dam could also change due to changes in precipitations and hydrology in the watershed [82].

Droughts can affect soil strength and cause erosion or subsidence, which can impact earth dams [103]. Embankment dams are also vulnerable to erosion caused by extreme fluctuations in water levels and changes in vegetation [113]. Dilatation and contraction rates of materials of the foundation and the components of dams can be impacted by the increased frequency of freeze-thaw cycles due to climate change [100]. For concrete dams, Alkali-silica Reactions (ASR, sometimes described as Alkali-aggregate reactions, or AAR) may increase with temperature. These reactions induce expansion and cracking in concrete, and can have severe impacts on the safety and functioning of existing concrete gravity dams and particularly spillway sections [114]. The literature did not describe what is being done to address the climate change impacts on these issues, or how well they are understood in the dam industry.

3.5 Adaptation Standards, Guidelines, and Best Practices

3.5.1 International Guidelines on Water Resource Management and Climate Adaptation

In ICOLD's 169th Bulletin, *Global Climate Change, Dams, Reservoirs and Related Water Resources,* three recommendations were provided for dam owners and the industry:

1. adopt a whole-of-system approach,
2. apply an adaptive management process, and
3. collaborate with a wide range of disciplines, interests and stakeholders [82].

The document presents a portrait of generalized risks and vulnerabilities of dams. Chapter 9 of the Bulletin provides adaptation principles and measures and presents six case studies across the world, recognising that adaptation measures will vary from one region to another. Emphasis is placed on the flexibility of infrastructures to evolve with climate trends (e.g. reservoir and discharge capacity increase) and functional adaptation measures (e.g. hydrological forecasting, improving operations and policies to reflect an integrated watershed management). This bulletin provides a useful starting point and foundational knowledge for dam practitioners in Canada, but does not provide enough specific guidance to inform an entire climate risk assessment and adaptation process.

The International Hydropower Association (IHA) has published a *Climate Resilience Guide for the Hydropower Sector* that is meant as general guidance for all types of hydropower projects [93]. The guide presents a high-level methodology consisting of six phases and numerous steps for climate risk screening, data analysis, climate stress testing, climate risk management, and monitoring, evaluation and reporting. An overview of hydrology is addressed in this document, including modelling, flood frequency analysis, and PMF. The practical approach presented is meant to address all hydropower projects, independent of size and geography.

Climate Risk Informed Decision Analysis (CRIDA), a report published by the United Nations Educational, Scientific and Cultural Organization (UNESCO), addresses Collaborative Water Resources Planning for an Uncertain Future [115]. This document complements existing national and international standards by addressing uncertainties, including climate change, for water resource management. The report proposes a methodology for risk-informed decision making that includes assessing and managing risk, but also communicating risks to stakeholders. This document is not specific to dam owners, but it contains a few mentions specific to dams including a case-study and examples of risks.

Climate Impacts on Energy Systems – Key issues for energy sector adaptation, a book published by the World Bank addresses the impacts of climate change on the energy sector and showcases different policy efforts and tools to support decision-makers in adaptation [116]. Among other suggestions, the authors present a climate risk management process to guide decision-making and the decentralization of hydropower production (i.e. smaller dams closer to the demand). The Asian Development Bank (2012) highlights that although there are broad policy intentions to begin integrating climate change considerations in Asia and the Pacific, little detail on methods and approaches to evaluate risk and develop practical action plans exist [112].

The United Kingdom's Department of Environment, Food and Rural Affairs has produced guidelines on the Impact of Climate Change on Dams and Reservoirs [113]. A list of risks specific to their geography and assets are identified and quantified, and guidance is provided to mitigate the risks.

3.5.2 American Guidelines on Water Resource Management and Climate Adaptation

Water resource management in the context of climate change is an issue addressed in the United States by several federal agencies [117]. A report was published in 2009 by the U.S. Geological Survey (USGS) that established the connections between climate change and water resource management [91]. Some of the key points highlighted in this report include:

- A need for long term monitoring of climate and hydrology at a large scale and in specific locations (e.g. near an important dam;
- The use of stochastic modeling and paleoclimate information to account for climate variability in long-term water management plan as a complement for historical data;
- The use of adaptative management techniques (decisions are made sequentially over time) in decision-making to enhance flexibility;
- Adapt dam infrastructures and operations to climate change; and
- Increase research and monitoring activities to fill knowledge gaps and limit planning uncertainties.

Following this report, the Climate Change and Water Working Group (CCAWWG) was created. It regroups multiple federal agencies, including the U.S. Army Corps of Engineers (USACE), the Bureau of Reclamation (USBR), the U.S. Department of the Interior (DOI), and the National Oceanic and Atmospheric Administration (NOAA). The working group produced two reports on the needs and gaps of climate information to guide short and long-term strategies, planning, decision-making, and policies [118] [119].

In the United States, high-consequence dam and levee failures prompted the Federal Emergency Management Agency (FEMA) to mandate the US National Research Council (NRC) to convene a panel of experts to address community resilience related to dam and levee safety [120]. Although not recommending policies directly, the report addressed methods of evaluating and implementing community resilience considerations in a dam or levee safety program. The report provided several conclusions applicable to the topics of dam safety and resilience in Canada in the face of climate change as well as other risks. It calls for a greater emphasis on systems analysis between infrastructure, watersheds, and the community; making dam break inundation mapping, emergency action plans, and risk information publicly available to support community resilience planning; and promotes the need for collaborative risk management approaches that include all stakeholders in a dam community including the dam and levee professionals and persons or entities exposed to direct and indirect consequences of a dam failure. This report also presented a tool to evaluate the maturity of community engagement in a dam or levee safety plan considering topics such as dam safety reviews, emergency action plans, floodplain management, and the degree of community involvement in each of these plans and in qualitative risk assessments. This tool may be applicable to the Canadian context, and a similar rating system could be applied to rate the maturity of climate change considerations in dam system management.

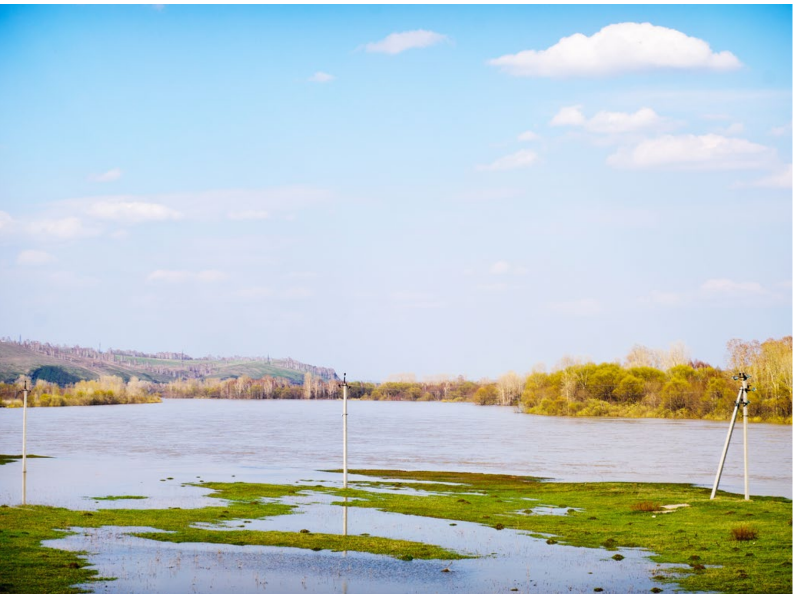
3.5.3 Climate Change in Canadian Codes and Guidelines

The following section showcases a non-exhaustive list of examples of how climate change is considered for hydraulic structures at large.

The Canadian Highway Bridge Design Code (CHBDC) [110] is a reference for the design of all hydraulic structures and can be used in dam design. Climate change is mentioned on several occasions throughout the document, including in Section 2, Durability and Sustainability, where it is stated that "the design shall include considerations for adaptation to local climate changes and anticipated impacts." Section 6, Foundations and Geotechnical Systems, mentions the need for a section on the groundwater elevations including anticipated fluctuations due to climate change. A consideration for climate change during site screening is also part of the permafrost design subsection of Section 6. A review of the impact of climate change on the permafrost conditions over the lifetime of the structure should be included in the geotechnical report. Finally, Section 15, Rehabilitation and Repair, mentions the need for consideration of the impacts of climate change in bridge rehabilitation. Interestingly, climate change was not mentioned in Section 3, Loads, which includes wave, wind, and ice loads. These requirements were not accompanied by specific direction on the degree to which climate change must be considered, the RCP that should be used, or other specifics that would be required to have a streamlined adoption of climate change considerations across the highway and bridge design industry. However, a new update of the document will address these concerns. The NRC and CSA conducted a research project and ongoing work to incorporate climate change adaptation into the next edition of the CHBDC.

National Standard of Canada's guide on Geotechnical Site Investigation for building Foundations in Permafrost Zones includes a mention to include climate change in higher risk projects, as well as a complete guideline on using climate projections [111].

Climate change is also considered in the engineering standards of the Quebec ministry of transport. Tome III – Ouvrages d'art [121] regroups all the standards relative to the design of bridges and culverts from the Ministère des Transports du Québec (Quebec Ministry of Transportation). In chapter two, the document states how climate change should be considered when calculating the design flow for bridges and culverts.



"The Canadian guidelines for floodplain mapping include considerations for climate change and case studies on climate change."

For watersheds under 60 km^2, the flowrate should be increased between 18% and 20%, depending on the location within Quebec. Flowrates calculated for watersheds between 60 km^2 and 400 km^2 should be increased by 15%. Lastly, for large watersheds of 400 km^2 and more, the flow rate should be increased between 0% and 15% depending on the general latitude of the watershed (southern locations surrounding Montreal requiring no increase in flowrate).

The Canadian guidelines for floodplain mapping include considerations for climate change and case studies on climate change [122] [123]. The *Federal Hydrologic and Hydraulic Procedures for Flood Hazard Mapping* provides guidance on how to address and model non-stationary processes like climate change, as well as documentation on the integration of climate projections on hydrology and sea-level rise. Uncertainty arising from climate change is recognised and several suggestions are made to address it (e.g. sensitivity analyses, risk-based approaches, security factors) [122]. Case studies presented in NRCan's *Case Studies on Climate Change in Floodplain Mapping* are useful for understanding the direct application of tools (e.g. software like HEC-RAS and HEC-HMS) and methods (e.g. IDF curves considering climate change or representing a range of scenarios on a map) [123]. EGBC has two reports presenting guidelines on flood mapping that include climate change considerations: *Flood Mapping in BC* [105] and *Professional Practice Guidelines – Legislated Flood Assessments in a Changing Climate in BC* [124]. This last report suggests a methodology to estimate future flood flows based on the presence or absence of historical trends in climate. If no trends are recognised, the guide suggests a 10% upward adjustment in design discharge. If a trend is recognised, the guide suggests an adjustment to flood magnitude and frequency related to the projected lifecycle change in runoff or an increase of 20% in cases of small drainage basins for which insufficient runoff information is known.

EGBC made a Climate Change Action Plan in March 2021 to guide and support their registrants to consider climate change in their practice [125]. Multiple actions are discussed, including the goal of providing practical guidance as guidelines and advisories on climate adaptation, based on feedback from registrants and stakeholders. EGBC is perhaps ahead of other provinces in providing their registrants with professional practice guidelines that consider climate change with documents like *Developing Climate Change-Resilient Designs for Highway Infrastructure in British Columbia* [126]. This document includes consideration for hydraulic sizing of structures like bridges and culverts and hydrotechnical analysis for bridges and dykes, as well as related hydro-climate parameters like snowmelt and rain. On the other hand, climate change impacts are not considered in the *Legislated Dam Safety Reviews in BC* professional practice guidelines [11].

3.5.4 Canadian Policies

The International Institute of Sustainable Development (IISD) proposes the ADAPTool to analyse policies with a climate adaptation lens [127]. An assessment of Saskatchewan's Water Security Plan (WSP) showed policies were able to address several adaptation needs related to dam safety, while other adaptation needs could not be supported by policies. A list of all the vulnerabilities to dams (mining, flood control, and hydroelectric dams) is presented, as well as adaptive solutions and how well policies of the WSP respond to them.

3.5.5 Identifying Regional Climate Trends and Risk Assessment Methodologies

A broad understanding of Canada's projected climate trends and risks can be found in *Canada's Top Climate Risks* [109], but it is not specific to dams. A local analysis of climate trends and hazard should be done at the forefront of new projects, as was done in Tajikistan and the Kyrgyz republic in 2009, even though the results of this assessment proved to have no impact on the design [112]. In ICOLD's 169th Bulletin on climate change, IPCC's method for regional impact analysis is recommended [82].

Another method used in Canada is the Public Infrastructure Engineering Vulnerability Committee (PIEVC) protocol. PIEVC was co-founded by Engineers Canada and Natural Resources Canada (NRCan) in 2005. The goal of the PIEVC is to assess the vulnerability of Canada's infrastructure to the impacts of climate change. They have published a protocol, available on request, to guide the assessment of the resilience to climate change of existing infrastructures. This protocol was used on two dams of the Toronto and Region Conservation Authority [96]. The protocol is a risk-based approach of five steps, including a risk assessment of interactions between the infrastructure and the climate, and an engineering analysis of the vulnerabilities identified [86].

While climate change is not directly mentioned in CDA's guidelines, chapter 6 presents a new risk-informed approach based on probabilities for dam safety that could potentially include climate uncertainties [7]. This section of the CDA guidelines was improved in the 2013 edition of the document. The traditional deterministic standards-based analysis is one of the steps of the risk-informed approach. Issues related to the risk-informed approach include current challenges in the characterization of hazards, of the dam system performance, and of the consequences. The traditional standards-based approach not only shares these difficulties but has several additional limitations including a focus on extreme natural hazards in isolation, which can lead to preferentially implementing less effective solutions.

Other risk-assessment methods are presented in international guidelines including the IHA and UNESCO reports presented in Section 3.5.1.

3.5.6 Estimating Climate Impacts to Inflow Design Floods

There is not a single method approved, validated, and used in Canada to account for climate change when evaluating the design flood for dams [80]. The existing guidance in provinces for calculating the IDF does not consider climate change, therefore engineers performing these calculations do not have guidance or consistent methods in achieving those results.

The Ministère de l'Environnement et de la Lutte contre les changements climatiques developed a web tool named *Atlas Hydroclimatique du Québec Méridional* that shows the magnitude and direction of the change in high and low seasonal flows for 1500 river segments in the Province [128]. This tool was not made specifically for the design of dams and does not address floods with a recurrence period over 20 years. However, it is a good example of how provinces can help in the estimation of flooding considering climate change.

Ouranos has produced two valuable documents that address this issue and that are specific to dams. The first one dates from 2015 and is on Probable Maximum Floods (PMFs) [79], and the latest was released in 2021 and was themed on flood frequency analysis [80]. A metric often used for determining the hydraulic capacity of dams is the PMF, the largest flood that could reasonably occur in a specific location [7]. Ouranos suggested a new method that integrates climate change (looking at the 2050 future horizon) to calculate the PMF for a watershed [79]. The method was applied to five watersheds in the provinces of Quebec, Ontario, and Manitoba.

In this study, the PMF was shown to occur when a spring Probable Maximal Precipitation (PMP) coincided with the melting of a 100-yr recurrence snow cover melt. It is expected that the recurrence of the PMP will increase, which would lead to an increase of occurrences for the PMF. The magnitude of the PMP and the snow cover could either increase or decrease, depending on the geographical location, but it was not uncommon that an increase in PMP was compensated by a decrease in the snow cover (especially for the most southern watersheds). Generally, the spring thaw for the 2050 horizon in the studied areas is expected to be between 5.5 and 9 days earlier, and the PMF is expected to change between -0.8 % and 20 % for the 2050 horizon. Ouranos also worked to develop methodologies of estimating the impact of climate change on flood frequency. The results included maps on the expected evolution of the thousand-year flood and decamillennial flood on 533 watersheds in Canada between the 1990-2010 and the 2080-2100 periods [80]. These maps are meant to be available publicly online in GIS format to be used as a tool or reference, but do not replace in situ analyses and do not cover all watersheds in Canada.

There is an international interest in the impact of climate variability and changes to the PMP, as is made evident by the state-of-the-art review on the subject by Salas et al. [129]. Methods presented are either based on hydrometeorological or statistics based. A section of this paper describes Canadian-specific guidelines regarding PMP and climate change, which predicts an increase in PMP. The American Society of Civil Engineers (ASCE) present several approaches to calculating the PMP with regards to climate change in a 2020 publication [129]. ICOLD's 170th Bulletin on Flood Evaluation and Dam Safety does not present a prescribed method to incorporate climate change in flood evaluations [83]. Key takeaways from this publication are that climate change may increase the uncertainty and variability of extreme floods in a way that will be hard to quantify. While estimating the changes in precipitation and snow cover is complex, once these changes are known, it can be straightforward to update hydrologic modelling, but can be expensive if models do not already exist.

3.5.7 Flood Control

The role of dams in flood risk mitigation is addressed in a climate change perspective in ICOLD's Bulletin on *Challenges and Needs for Dams in the 21st Century* [130]. The report mentions current dams' crucial role in defence against flooding by storing surface water run-off. More recently, ICOLD has created a committee on levees and flood defences. Such a committee does not exist in CDA.

3.5.8 Hydropower Production

There are different examples of hydropower production adaptation in the literature, but it requires good information and certainty of the changes coming. A 2009 study on this subject presented a methodology that used climate change projection scenarios in a profit optimization model to adapt operating rules of a water system [99]. By optimizing management, the modeller was able to achieve an increase in hydropower profits from the year 2030 and onwards. Another example from Landsvirkjun, the National Power Company of Iceland mentioned in Section 3.4.2.2.5, is notable in that not only were operations adapted to increase generation, but the design capacity of future plants consider the projected increase in runoffs [97]. The impact of hydrology changes on energy generation and power output of hydropower plants and the effect it has on revenues is explored in Ouranos' work, *Valuation of Hydropower Assets and Climate Change Physical Impacts: A Guidebook to Integrate Climate Data in Energy Production for Value Modelling* [100]. This work is a useful reference for hydroelectric dam owners.

Ice booms could also be gaining field to ensure hydropower production throughout the winter. Seven ice booms were used in the Beauharnois canal to facilitate the formation of an ice cover and ensure generation at a downstream hydroelectric dam [131]. Ice booms are also used on the Saint-Lawrence and Niagara rivers [132].

3.6 Limitations of Literature Review

This literature review included few international standards but focused mainly on the most relevant information on climate adaptation for dams in Canada, and therefore had some limitations and gaps. There was a lack of available or reliable data for certain dam-specific impacts from climate change. For example, a quantifiable link between the impacts of ice in rivers in Canada and climate change has not been solidified through observations. There was limited literature on the direct impacts of climate change on the construction phase of dams. There were instances of limited or no access to documents, specifically federal or private organizations' internal documents. Other topics that could be relevant to a more general discussion on climate change but were too specific or narrow in focus to be included in this scope include climate change impacts to water quality, thermal impacts to concrete dams, monitoring of structural performance in future climates, climate impacts to dam foundations and seepage, and combined or indirect impacts to dams. Indirect impacts such as the effect of a changing climate on ecology (e.g. algae) in a dam system and the impacts of minimum flows on fish species were out of scope as well as tailings and mining dams.

4 Stakeholder Engagement

Based on the discussions that occurred in stakeholder interviews and the workshop, the findings of the stakeholder engagement have been organized into four major sections — 1) the principal climate risks identified; 2) climate adaptation initiatives; 3) barriers to adaptation; 4) the need for climate adaptation guidance. The interviews intended to gather information on climate change risks to dams, adaptation actions and barriers to act. Discussions in the workshop validated the preliminary findings of this research, expanded on key topics, filled gaps in the research, and identified new considerations that had not been reviewed or discussed. This section consolidates results obtained during the interviews and the workshop.

4.1 Key Climate Risks

Most interviewed experts agreed that there was a lack of knowledge and data on the risks of climate change for dams and an assessment of the vulnerability was identified as a first step in the process of resilience and adaptation.

There were several climate risks identified by participants as potential for concern, some of which were universal to most dam owners interviewed across the country. Extreme hydrological events and flood control was identified as the primary concern by multiple private and public dam owners, especially if run-of-the-river dams were part of their assets. Operating challenges caused by climate trends leading to changes in regular operations were also mentioned. These may include changes to the timing of the freshet or one with higher peaks, combinations of snow and rain, more frequent seasonal high flows including in the winter, drier summers, and the absence of ice cover leading to frazil ice production. These changes in demands on the dam system could require a modification of the operating curves, which can be difficult to alter due to the numerous stakeholders involved along with the requirement for regulatory review and approval. In the summer, it may become harder to respect the minimum flow requirements for dams that depend on natural inflows. More frequent operations also add a stress on the mechanical and electrical components that may not have been accounted for in the design. When more operations occur in the winter, icing and cold can affect the equipment and its functionality.

Stakeholders expressed concern that climate change could exacerbate maintenance and operations failures prior to presenting conditions that would surpass dam designs. Large dams are designed for extreme conditions (e.g. 1 in 10,000-year precipitation events), and some stakeholders felt that the impacts of climate change within the intended lifespan of these dams would be minimal. Others thought that there was not enough information or that the information available lacked precision, quality, or exhaustiveness to disregard the risk that climate change presents to large dam designs. The potential risks to small dams that may be designed for shorter return period precipitation and flooding events such as the 1 in 100-year event were also discussed. Some stakeholders expressed that these events are becoming more frequent, and therefore the actual 1 in 100-year flooding events may need to be revisited to prevent dams from potentially being overwhelmed.

Other climate risks that could impact dams across Canada include changes in temperature impacting operations. Some dam owners have seen an increase in temperatures in powerhouses, which can impact worker comfort, safety, and equipment tolerances, leading to required HVAC upgrades. A potential issue for public safety across Canada is the impact of climate variability on hydraulic jumps downstream of low head weirs, dams needing to be operated more frequently, or remotely operated dams. There was also a concern that if there is a large failure of one dam due to climate change there may be reputational risks to the entire dam industry. Much like other large industries (e.g. nuclear), a single 'weak-link' in the industry could disrupt public and governmental confidence in dam design and operations.

Some important climate risks were specific to certain geographies, including forest fires in Western Canada. The change in landscape and the impact on flooding as well as management of debris after forest fires poses a risk to dams. Similarly, permafrost degradation and soil stability in northern regions was identified as a structural concern by researchers interviewed. Permafrost remaining frozen has been assumed to be constant for stability of some dams, which may not be the case as temperatures increase. Access to dams for maintenance in northern regions was also a concern; some dams may only be accessible by ice roads in the winter, which are already seeing shorter windows of operations and disruptions. If these windows are further or continuously disrupted, the ability to perform regular maintenance may be jeopardized.

Potential climate impacts on generation could result in loss of revenues from droughts and intense floods exceeding generation capacity for hydropower facilities and failing to meet the demand in isolated communities relying on hydropower for energy supply. In the prairies, there was more of a concern with drought than other climate issues and how this might impact water supply for irrigation. The resilience of communities in this region may depend on a water dam for irrigation or water supply, which could be impacted by climate change. If water consumption increases along with temperature, this could apply stress to the water supply system and associated watershed. Another unique consideration in the prairie regions was the surface area of the watersheds and the low slopes of the rivers. This means there is significant upstream intervention in the watercourse and therefore difficulty in interpreting climate changes separately from human intervention. Lastly, hurricane activity in North America can impact climates in Ontario and other Canadian provinces, and this interaction is not well understood. Improved forecasting tools and climate measurements are important for managing dams now and in the future, as these events change.

4.2 Climate Adaptation Initiatives

While some attention was given to climate change and actions were undertaken in many of the organizations that participated in the interviews, there was in many cases an uncertainty and lack of expertise on best practices for implementing climate adaptation measures to dams in Canada. Although every interviewed stakeholder was at a different place in their journey to adapt to and address climate change and many were near the beginning, several initiatives were presented by stakeholders who have taken action to address climate change impacts to dams.

Certain large dam owners, or owners who were part of a larger organization, have done work to educate their staff and integrate climate change throughout their company and operations. They have found that training people to apply that knowledge has come with a long learning curve. Some larger organizations are driven to exceed provincial standards and regulation in climate adaptation by internal organization initiatives, investors, insurance companies, extreme events, or expected changes in generation profits. Larger dam owners and utilities have created working groups on climate vulnerability and resilience. Based on their findings, an important first step is to assess the risks and vulnerabilities of their assets to climate change.

Some utilities interviewed were looking to prepare a toolkit and methodology that can be systematically applied to new projects to ensure uniformity in the organization with respect to climate risk. One such initiative that was being used by a utility includes a vulnerability assessment toolkit inspired by the PIEVC [133] and CRIDA [115] frameworks, a climate atlas providing climate projection data specific to owned assets, and climate adapted intensity-duration-frequency (IDF) rainfall curves. Some interviewees expressed concern that the PIEVC protocol for climate vulnerability assessments is more suitable for infrastructure designed for climate events with return periods of 1 in 100 years, and not dams that are often designed for more extreme events. It was also noted that the PIEVC protocol is a useful reference for dams but does not adequately address the varying risk levels between extreme events and more frequently recurring ones. Other risk assessment tools being used by stakeholders included: Hazard Identification Risk Assessment (HIRA) process to qualitatively assess risks, their drivers and indicators; an approach that had new projects review future climate projections to identify whether there could be any issues or changes required to design; and a portfolio-level risk identification approach to focus in on the highest risk hazards or assets across the portfolio.

Interviewed dam owners and utilities had in some cases consulted with external firms on the climate resilience of some of their new or existing projects with specific vulnerabilities (northern climate, prone to flooding, etc.). There have been mixed results, with some external companies not having the knowledge to integrate climate change into their modelling. Other dam owners have benefited from existing work conducted by their parent organizations such as existing adaptation plans or local projections that could be applied to their dams.

Modifications to dams to increase reservoir and discharge capacity were used by some interviewees as a response to extreme events and dam safety reviews results, which could become increasingly necessary with climate change.

Organizations like the CDA and ICOLD, along with associated events and technical bulletins, were cited as effective mechanisms for advancement of best practices and knowledge sharing of climate change adaptation measures as new climate change information becomes available and the understanding of climate risks to dams grows. Some organizations have supported research on climate adaptation for dams conducted by Ouranos2F[3], an organization identified as a valuable ally in this effort.

Lastly, some interviewees felt that the most appropriate climate adaptation initiatives should result from individual engineers taking responsibility to identify the risks to the infrastructure that they are working with, which should include climate risk.

4.3 Barriers to Adaptation

In individual and group stakeholder discussions, the availability of climate data was described to be an important issue for climate adaptation for dams. Limited access to reliable data, or capabilities to interpret available climate projection data were identified as the most significant barriers by most stakeholders. As a result of the data limitations, some stakeholders felt that it was hard to differentiate real climate trends from weather uncertainty. Data acquisition and research on extreme events (notably PMP and PMF) were of particular interest to stakeholders. Although water monitoring services and data are available to differing degrees across provinces, stakeholders felt that identifying research and organizational gaps would be facilitated by an increased availability and quality of climate data across Canada. Interestingly, stakeholders in the research and federal space said that there was a lot of data, but that there was a disconnect in providing access to end users both in the right space and format.

There was also a lack of consensus on the validity of available climate change projections and their applicability to dam design and operations. To get good quality data with lower uncertainty, it is important to get data from different climate models rather than a single one. National data sources are used for regional climate projection data, but the methods used for downscaling differ. Therefore, a procedure for downscaling could help the dam industry to provide uniformity across regional models.

3 https://www.ouranos.ca/en/

It was also noted that implementing projected climate data, interpreting its quality, and applying sound methodologies in doing so is outside of the capacity for some organizations due to a lack of qualified personnel, making it difficult for dam owners and practitioners to act on climate adaptation. It requires a thorough understanding of climate science to appropriately interpret and downscale global, national, or provincial data to specific locations. Additionally, where site-specific climate projections are available, it can be difficult to interpret this data and translate it into direct impacts to infrastructure and operations, and determine appropriate adaptations with confidence in justifications. Therefore, dam owners may need to use external consultants to understand climate risk, an expense requiring justification to investors, rate-payers, or other stakeholders.

Another important barrier is the utility of climate data being developed and modelled, and how this relates to the end user's needs. Data sources, formats and interpretation methodologies must be applicable in informing design, operations, and maintenance decisions. Useful data formats and education on how to use the formats available could be facilitated by stakeholders and disseminated through standards-based solutions. There are also efforts in the research community to provide services connecting climate data to its application in engineering. This would address many issues that stakeholders noted. Researchers have assisted the bridge and buildings industries in developing models practitioners can use to adapt infrastructure for climate change. Similar projects could be undertaken for the dam industry.

The general mindset for dams engineering is currently deterministic (where studies provide a single answer), but this needs to shift to probabilities, statistics and risk-based analyses to be able to appropriately incorporate climate change. The predictive and uncertain nature of climate change requires a range of results to be evaluated. This means decision-making must also follow acceptable risk tolerances, which some organizations and practitioners are not familiar with. Interviewees mentioned that most practicing engineers lack formal training in designing for uncertainty, risk-based decision-making, and interpreting changing climate conditions as well as climate projection data. They also said the engineering practices and standards currently being used for the most part do not include consideration of climate change adaptation.

Lack of financial incentive and cost-benefit data on adaptation investments was identified as a potential barrier to adaptation for smaller dam owners. They must spread resources across their assets to ensure that they are all safe, operating as intended, and in line with industry as well as stakeholder requirements and expectations. As per many stakeholders, the current limitations of climate data, and the lack of understanding of climate risks and practical adaptation measures are impeding the appropriate justifications to support the costs required for adaptation. This was notably less of a concern among larger dam owners and those with government support or mandates.

Some interviewees felt that the industry can often be siloed and has been slow to embrace the systems approach to dam management, which would be necessary in working towards resilience. Interviewees expressed concerns over the challenge of coordinating adaptation efforts across multiple owners and operators in a single watershed. For instance, multiple agencies must often work together in the larger watersheds both from an operational and monitoring perspective as well as public communication and safety. Poorly coordinated efforts could exacerbate the impacts of climate change. This was identified as a potential topic to develop guidance on best practices for watershed management in the face of climate change and uncertainty.

Concerns over competing jurisdictional and regulatory boundaries and considerations were discussed, namely that water and dams have always been provincial mandates and do not fall under federal purview. In addition, some provinces have different ways of classifying and managing dams such as using a river system or watershed approach. This may complicate how climate adaptation can be incorporated across the industry. Any type of regulatory enforcement would require that a standard be adopted and integrated into existing provincial frameworks. Regulators interviewed indicated that policy is typically created in response to an incident or a growing understanding of an issue.

"There was consensus about the importance that dam owners understand the risks and vulnerabilities of their dams in order to determine acceptable risk levels including climate risks."

In Canada, there have not been many dam incidents directly attributed to climate change, and the common understanding on how climate risk should be managed is not yet clear. Therefore, policy is more likely to be reactive to trends in the industry as best practices or climate risks become more evident.

4.4 Climate Adaptation Guidance

The solutions that the dams industry needs to adapt to climate change are not simple. The stakeholder engagement provided some perspectives in favour of standards-based solutions and some concerns.

A general need for support in climate change adaptation has been identified amongst most stakeholders. There was consensus about the importance that dam owners understand the risks and vulnerabilities of their dams in order to determine acceptable risk levels including climate risks. Among those who had not yet formally considered climate change in their designs or operations, most were aware that climate change may impact their system, but did not know how and to what magnitude. This uncertainty was concerning to some. The need for general guidelines or best practices on the methodology to integrate climate change in projects, to use and interpret data was mentioned. Other topics included specific guidelines on floods, droughts, or safety, and guidelines on resilient design. It was specified that using blanket statements, rules, or specific values would not be applicable nationally (e.g. 8% increase to the current 100-year flood to account for climate change), but that defined methodologies, considerations and best practices could be useful. Further, some expressed that language generally defined in standards could help ensure consistent methodologies and implementation across the industry, rather than using guidelines that can leave more room for interpretation.

Conversely, concerns were expressed with implementing standards-based solutions. Some interviewees mentioned potential challenges with the logistics of applying a national standard or guideline for climate adaptation in an industry lacking national standards for dam safety or other related topics beyond provincial regulations and national guidelines. Some supported solidifying climate change adaptation best practices with dialogue and education through conferences and research publications, and allowing for interpretation and prioritization to suit conditions of dams and dam owners across the country. Some felt that current CDA guidelines offer enough safety and resilience for dams regarding climate change; others wanted more research or discussion of risks, vulnerabilities, and climate adaptation measures to justify the need for adaptation. This could be addressed by further research specific to dams, or increased dissemination of the information already available on this topic to stakeholders.

There were recurring themes on what stakeholders thought would be useful tools. Some included guidelines and decision-making tools to interpret climate projection data and quantify impacts on assets due to climate change, along with a tool to update operating procedures in response to expected climate changes. Many suggested a standards and guideline able to account for the variability and scope of dam designs, locations, and operations, as well as the geographical variability of climate across the country, could be a very useful reference. Some interviewees recommended integrating standards or guidance within provincial laws and guidelines to allow tailoring to provincial climate risks. For dam owners at the beginning of their journey towards climate adaptation, a road map of how to address climate change for dams could make a significant impact. Yet, it would likely not impact those who have already begun adapting.

Stakeholders also stressed the importance of considering climate change as one of many priorities for dam owners to ensure a resilient system. It was suggested that climate adaptation for dams could be an add-on to existing guidelines or DSRs so climate change can be viewed as one of many uncertainties faced by dam owners. A standard or guidance should ensure that climate change is considered alongside other priorities including operations and maintenance. This is to ensure budgets, especially for small dam owners with strained resources, can be allocated appropriately. Similarly, a dam is only a single component of a larger system and a standard or guideline should consider the reservoir and physical operating requirements, and organizational procedures surrounding the dam to provide resilience in climate adaptation measures. An example was provided where some electrical equipment was not designed for extreme cold; this impacted the discharge capacity of the dam.

Some stakeholders stated that given the relatively short dam safety review horizon compared to climate change, a significant variation in conditions would need to occur to approach surpassing the design envelope of dams within their lifespans. Currently, decisions are made based on historic climate conditions and events. Yet, climate change warrants consideration of future potential risks and designing for uncertainty rather than past and current conditions. Although the impacts on dam design is disputed by stakeholders, most agreed dams operations may be impacted by climate change within the lifespan of the infrastructure.

Some needs that stakeholders mentioned would be most important to address included guidance on processes for climate data acquisition and interpretation; how to address data confidence and quality; how to be transparent in the source and validation of the data being used; on managing uncertainty in data and decision-making; and guidance on adaptation measures that have been applied in the industry so that other stakeholders can benefit from these learnings.

5 Discussion

5.1 State of Knowledge and Gaps

As discussed in Section 3.5, there is guidance on how to account for climate change in the design, operation, and maintenance of infrastructure in Canada that is not specific to dams, and some international guidance that is specific to dams. The international guidance is a useful starting point but needs to include detailed regional climate data and site-specific risk analysis. Guidance not specific to dams can also be a good tool, but risks associated with dams can be very different from other infrastructures, especially regarding public safety. As an example, flood recurrences used to design dams are much higher than those of bridges or culverts. Hence, organizations are developing their own documentation and guidance to address climate adaptation for dams, which could lead to differences in methodologies between industry, governments, small dam owners, and utilities.

Several barriers to the adaptation of the energy sector to climate change were highlighted in the literature. They include lack of technical guidance, insufficient institutional guidance, climate projection uncertainty, and lack of a rationale for investment [97]. These barriers were validated during the stakeholder engagement process (See Section 4). Most dam owners felt there was a lack of uniformity in the availability and quality of data in Canada, no expertise in interpreting and processing the climate data yet, and no standardized approach within companies or across the industry for dealing with climate change in their assets and projects. Notably, it was stated that established parameters such as frequency analysis of hydro-climatic data may have shifted in ways that are difficult to predict and therefore are not being considered currently. Multiple interviewees felt that practicing engineers lacked the formal training in addressing uncertainties in design, risk-based decision-making, and interpreting changing climate conditions and climate projection data.

As for the general concern regarding data limitations, the stakeholders from the scientific and research communities felt that Canadian climate trends were known and available at a regional level on websites such as climatedata.ca [134]. Dam owners and engineers are usually well equipped to manage known and well understood hazards and risks of their assets. Therefore, the gaps identified are the knowledge of available data sources, the ability to evaluate data quality and usefulness, the ability to interpret available regional climate data to site, or watershed-specific hydrology and weather events, and how this information can be used to inform site-specific climate adaptation decision-making.

5.2 Motivation for Climate Adaptation Implementation for Dams

Stakeholder interviews demonstrated a general motivation to consider climate change in dam-related projects. Private dam owners and utilities mentioned receiving pressure from shareholders, investors, the public, and insurers to manage financial and physical risks associated with climate change. While planning the Keeyask Generating Station by Manitoba Hydro, for example, the licensing process and discussions at public hearings showed that stakeholders were sensitive to climate change and valued careful planning of adaptation to it [97]. A small dam owner providing electricity to an isolated microgrid in a northern community mentioned that climate change could be a threat for the reliability of the electricity service and therefore the community's resilience. Several organizations consulted had already moved forward in addressing climate adaptation, but many were still at a preliminary stage of identifying vulnerabilities in their systems. Some had started to research data and develop tools for assessments and adaptation, but none had a uniform approach throughout their organization for considering climate change and implementing adaptation measures.

Another incentive is the Engineers Canada recommendation to consider climate risks and inform clients of climate adaptation measures in *Principles of climate adaption and mitigation for engineers* [135]. Multiple risks and adaptation measures for dams in Canada were identified in the literature review and during interviews. Some of the risks identified could potentially impact dam safety within this century, which provides reasoning for dam owners to be aware of these potential risks and to act if necessary.

In their Climate Change Action Plan, EGBC identifies the development of "practice guidance" on climate change considerations as one of ten actions to support their registrants [125]. According to the report, "it is no longer appropriate to base engineering and geoscience practice solely on historical climate data and methods." The EGBC has also gathered resources relating to climate change considerations for design and adaptation of various types of infrastructure on their site. Some of these resources are EGBC-created guidance documents, others are gathered from other agencies and data sources for reference when working in climate adaptation. These resources can be a starting point for practitioners wanting to consider climate change in their designs, but do not provide dam-specific guidance or indication on how to interpret climate data in every setting. This compilation of resources could, however, be an interesting model for the dam industry to follow.

Based on the identified gaps in the industry and stakeholder needs, a standard or guideline could be helpful to assist organizations without internal climate change expertise and ensure uniformity and safety in dam design and operation.

5.3 Topics for Guidance and Research

The consultation process identified that guidance, education, and industry discussion would be helpful in guiding organizations that required support in achieving a minimum level of climate resilience. However, any formal industry guidance would have to address the barriers identified in Section 4.3. For example, a guidance document would require regular updates to reflect the dynamic context of climate change and climate research. This section discusses topics that could benefit from guidance, as guidelines or standards, and topics requiring more research.

Significant climate trends have not been and are not expected to be observed in less than 30 years [37]. The CDA recommends re-evaluating the IDF following extreme hydrological events [7], or every five to ten years as part of the DSR program [136]. Since IDFs are based on historical data, climate change has not yet contributed to significant changes to IDF and design flood modelling. Currently, the process does not require consideration of future climate projections as part of a DSR because these reflect only the present condition and code conformity of the dam. This could be addressed in a guidance document to provide support in evaluating the impact of climate change on the IDFs, and on identifying and quantifying other changes to design loading. The documents cited in this report (i.e. [79] [80] for the inflow design flood and [96] [115] [93] for risk-assessments) provide a useful starting point. However, specific guidance on data acquisition, interpretation, and regional trends across Canada would require additional research.

As a result of expected climate changes, increased variability in weather events may lead to changing demands on operations, surveillance, maintenance, and emergency response planning. Special considerations may be needed for aspects such as:

- Operability of intake and gate equipment during winter;
- Equipment wear from more frequent usage;
- Occurrence of forest fires and the impact on the upstream landscape;
- Increasing water supply demands;
- Difficulty maintaining water levels within small operating bands; and
- Increasing reliance on waterpower for flexible energy generation involving changes to current reservoir operating models, sedimentation, and permafrost melting in northern region dams.

Small dam owners with low-consequence assets requiring no dam safety revisions with a 100-year return period IDF may also be concerned with underestimating risks if not updated as climate science continues to progress. This particular issue warrants further study to understand the potential unknown risks to small dams as limited literature was found on this topic. This was identified as a knowledge gap among stakeholders.

Researchers indicated that useful climate data is currently available; yet, stakeholders said they either did not know what data was available, how reliable it was, or how to apply it to their systems. In fact, concerns were expressed about the knowledge gap of the entire climate vulnerability assessment and adaptation process. This gap runs from climate projections and risk assessments to decision-making and adaptation actions. These concerns could be addressed in a guideline or a standard presenting an industry foundational knowledge base in the interpretation of climate data, risk assessment, and adaptation processes.

The needs for addressing climate adaptation to the operation and safe management of existing dams are significantly different from the studies warranted for new infrastructure or major projects. Capital planning and DSRs ensure that dam owners have a strong understanding of the principal vulnerabilities of each of their assets. Dam owners said they are aware of which issues are most important for the safe management and operation of their dams. Such issues could include recurring problems such as difficulty in achieving minimum flows in dry seasons, a list of priorities for rehabilitation like ageing infrastructure and equipment, or PMF flows nearing the spill capacity. Therefore, useful guidance could focus on potential issues and vulnerabilities that may occur in various regions, and how these may be exacerbated by climate change. For instance, a dam owner who has issues meeting minimum flow requirements in summer may decide to look further into drought if this issue is projected to increase in their region. Similarly, dam owners with only one access route to their sites might study the probability of extreme storms in their area and plan for potential road washouts if applicable. Guidance highlighting climatic changes and hazards for dam owners and practitioners to anticipate, and instructions on appropriate risk management might help identify potentially exacerbated vulnerabilities and the need for further study.

Another important point is that dam owners must contend with many differing priorities. Climate change is only one factor amongst others that may present a risk to dams in Canada. A risk-based approach for decision-making would allow for the dam industry to accurately compare the consequences and benefits of asset management and operations priorities in relation to climate adaptation needs. Despite challenges in data availability and interpretation to the asset-specific context, once climate risks have been identified, the value of implementing climate adaptation measures could be compared against other priorities. Guidance for practitioners on how to conduct a system-wide risk assessment could be useful alongside advice on how to incorporate climate risk into such assessments.

The European Committee on Standardization developed a general guide for creating new climate adaptation standards [137] that is not aimed specifically at dams or infrastructure projects. It includes a decision-tree to help determine what should be included in a climate adaptation standard. Applying this methodology, a new climate adaptation standard for dams in Canada could include the following:

1. A range of adaptation measures to consider in the design of dams. These include options beneficial even without climate change (i.e. improvements to operations and monitoring),
2. Projected changes to climate conditions over the lifetime of dams based on relevant parameters (e.g. hydrology, ice, run-off, forest fires, temperature) including uncertainty,
3. Climate trends, reference documents and climate projection data sources for the time period relevant to dam infrastructures (to replace existing climate information),
4. Guidance on methods to apply future climate projection data to a site to inform decision making (e.g. calculate design floods, reservoir levels, ice and wave loads, run-off and sedimentation),
5. Defined levels of risk or impacts for which dams need to be resilient. These levels would consider mitigation measures in place, designing for exceedance, designing for degrading performance and provisions — for example, supply and access routes, extra sandbags and flood mitigation measures, water agreements with other cities in case of a drought, or redundancy— and,
6. Estimated period of validity for climate information and regular updates of standards to include new research.

In summary, the suggested standard on climate adaptation for dams could identify sources of hydro-climate data, how to use and interpret data, quantify risks, define acceptable levels of risks, guide decision-making, and suggest best practices in adaptation. But, given Canada's wide-ranging geography and varying levels of data availability, site-specific impacts of climate change to dams (and in many cases their remoteness), it may not be practical for a standard to provide climate change projections and sources (items 2 and 3 above) adequately applicable for all dams in Canada. The other items could be generally applicable nationally. Yet, they would need to carefully consider the wide variety of dam functions and constructions. These concepts are discussed further in the sections below.

5.4 Process for Climate Adaptation

Based on conversations with dam owners, practitioners, and climate adaptation specialists, a general process to address climate change risks and adaptation practices for a dam system in Canada has been developed. The intent is to provide a structure for discussing current practices for dams, gaps in resources, and potential next steps for the industry to move towards climate adaptation. Although dam owners would not own the entire process, some steps would need to be driven by them and supported by others (consultants, researchers, industry organizations, and standards development organizations). The suggested process includes six steps:

1. **Determine local exposure to climate change:** The first step is to identify the issue, and determine how and to what extent climate change is expected to impact dams in Canada. As discussed in Sections 3 and 4, there is a common understanding that climate change will impact the climate and weather systems in Canada. It is expected to bring higher average temperatures, shift precipitation regimes, increase variability, and exacerbate some weather extremes already seen across the country. Since the function and operation of dams rely on the water cycle and other environmental factors, changes to those systems will also impact dams. However, the type and magnitude of these climate changes and weather patterns will vary geographically. Therefore,

so will the impacts. Varying degrees of climate data exist across the country for both historic trends and climate change projections [37], along with multiple methods of interpreting the data from climate models to a specific site. So, there is a need to study the site-specific climate conditions projected for specific locations or regions rather than looking at national trends.

2. **Assess potential impacts to infrastructure and operations:** Once the projected changes in climate for an area are established, dam owners and practitioners can determine if and how these could impact the dam infrastructure and operations. Potential impacts will differ for each dam depending on size, location, infrastructure type, age, purpose, etc. Therefore, understanding each dam system and current issues or vulnerabilities at the site are important in order to identify how climate change may exacerbate these vulnerabilities or present new risks. Changes to PMFs have been studied for a number of watersheds across the country. Findings show some design floods are expected to increase, and others are expected to decrease with varying magnitudes [79]. This demonstrates the need for site-specific interpretation of climate data to determine how changes to rainfall and snowpack will impact the expected PMF at a dam.

   The application of climate change projection data to design flood models requires specific experience or extensive study in the field, a large data gap for most owners and operators. Once site-specific climate parameters are known, there are some tools available to support practitioners in assessing risks and impacts to a dam system, such as the PIEVC protocol. This could be adapted to consider the uniquely high consequence levels associated with risks to dams [138], the Failure Modes and Effects Analysis (FMEA), or the Potential Failure Mode Analysis (PFMA) program from the US Federal Energy Regulatory Commission (FERC) [139], which could be adapted to consider climate change.

3. **Evaluate risk:** Having established the impacts climate change may have on a dam system, the risk associated with each potential impact can be assessed by determining the likelihood and consequence of each potential impact. The ISO 31000 Risk Management standard can guide this process [140]. Climate change risks can then be prioritized and compared to other risks on site or in an assets portfolio to find if and where design, operations, maintenance, decision-making, or capital planning should adapt to climate change. Stakeholders stressed the importance of having a system-wide understanding of all risks to dam infrastructure and operations. If current decision-making does not consider non-climate related risks, it would be difficult to appropriately prioritize climate adaptation against other improvements and maintenance to a dam system.

4. **Compare expected changes to existing vulnerabilities:** If system-wide risk assessments are not feasible either due to limitations in resources or in-house expertise, the site-specific climate projections can be used to assess potential impacts to dam infrastructure or operations. This can be done by determining where these changes may exacerbate existing vulnerabilities. This will help dam owners identify where to allocate resources for further study. One organization interviewed had used site-specific climate data to perform a “stress test” assessment, using expert judgement to identify whether projected changes might lead to significant impacts to their infrastructure or operations with the intention of studying these areas further.

5. **Evaluate adaptation measures:** Knowing the climate change risks and potential impacts on dam system, system resilience can be evaluated and vulnerable areas identified. There may already be redundancy in the dam system and operations or monitoring and mitigation procedures enabling a resilient system. Where climate risks are not already being managed, monitored or mitigated, potential adaptation measures can be evaluated.

   Adaptation solutions should consider physical improvements (i.e. adding redundancy to site access routes); changes to operations (i.e. responding to more frequent or more sudden operation needs); adaptation to procedures (i.e. updating operations, maintenance and surveillance plans to monitor key climate indicators); and organizational changes (i.e. employing operators year-round to manage new demands on winter operations).

"Climate change should be considered in the design, operation, and maintenance of dams, while remaining consistent in approach and appropriate to the type, size, and consequence level of the dam."

Adaptation measures can then be prioritized based on the actions that provide the highest value with respect to their impact on the resilience of the overall system, public safety, the organization's priorities and resources, effectiveness of measures, etc. For a dam system to be resilient to climate change, there should be alignment in the adaptation planning for the infrastructure, operations, and organization.

6. **Continuously update assessment:** Since climate change science and data are continuously changing and updating, climate risk assessments and climate adaptation planning and prioritization may need to be revisited after a certain time period, which could be based on the consequence level of a dam as per DSRs.

These steps remain general and do not provide specific actionable recommendations that can be applied by the dam industry.

5.5 Recommendations for the Dam Industry

Guidelines and standards addressing climate adaptation for dams applicable to the Canadian context were not found in the literature review and there is no consensus on best practices amongst stakeholders consulted for this project. Dam owners and other stakeholders differ on the process of addressing climate risk to dam infrastructure. Many dam owners have not taken steps to adapt to or assess climate risk to their infrastructure due to the lack of incentive, lack of resources, or a focus on other priorities. Considering the potential for climate change impact on dam designs and operations, and the inconsistent treatment of the issue in Canada, guidance is needed on how to adapt to climate change and what the industry can do to ensure appropriate climate risk management for dams.

Climate change should be considered in the design, operation, and maintenance of dams, while remaining consistent in approach and appropriate to the type, size, and consequence level of the dam. The following recommended actions provide a road map towards climate adaptation to address current barriers and seize opportunities for industry alignment:

1. Assess and address climate change data needs for dams through research and collaboration.
   a. Determine the type of climate projection data needed by the end users (dam owners, consultants, operators, regulators, researchers) and which metrics are most useful for climate risk assessments and adaptation. This includes considerations of acceptable geographic and temporal granularity as well as the delivery method (e.g. GIS) best suited for use by end users.
   b. Develop a standardized methodology based on best practices to facilitate interpretation of climate change projection data to the site or watershed-specific level. Current climate change data analysis requires expertise in climate science to make appropriate assumptions and interpretations. More research should be conducted to establish a clear methodology or

best practices that can be applied to different data sources and adapted to dams across Canada. Strong collaboration between climate scientists and dam industry practitioners would be key to accomplishing this task. Guidance should be a balance between firmness to prevent misinterpretation of data and agilility to respond to changes in the industry as climate data continues to evolve and develop.

c. Conduct a geographic gap analysis to determine where data is insufficient to perform climate risk assessments.

2. Establish best practices and develop a guidance document for conducting climate change vulnerability and risk assessments for dams.

a. Develop a standard or guideline for assessing climate risk and vulnerabilities based on existing risk assessment methodologies (such as the PIEVC Protocol or ISO 31000 Risk Management) and adapted for dams, or on existing dam safety failure mode assessment methodologies (such as a FMEA) with the inclusion of climate risk. The document should rely on the experiences and lessons learned from practitioners who have already done such assessments along with input from other experts in the industry and the research community. Consultation would be critical to ensure the level of detail proposed for this assessment is feasible for end users.

b. Establish best practices for estimating the impacts of climate change to design floods through further research and development. For instance, some regions in North America have adopted a standard percentage increase in the design flood to account for climate change [124]. More research should be conducted to determine the geographic scale at which this could be appropriate for dams in Canada, or develop a common methodology to determine climate impacts to design floods in a watershed.

c. Identify a list of potential climate change impacts to dams that practitioners can account for in a vulnerability assessment based on geography and type of dam. Many of these have been presented in this research. A complete list can be developed through further stakeholder consultation.

d. Establish guidelines or a standard for the consideration of climate change in new developments and major projects. These projects could see future climate parameters included in design criteria and considered in design decision-making. This warrants different language and climate risk considerations rather than assessments of existing infrastructure.

3. Establish best practices for climate and non-climate related risk-based decision-making for dams.

a. Define acceptable metrics for rating climate risk for the various types of dams and their consequence levels through research and consultation. Risk tolerances vary across organizations, and risk levels increase with the consequence level of a dam. Extensive consultation with stakeholders, regulators, and the public will be required. The aim is to determine whether risks should be rated relative to the other risks in a dam system, the risk tolerance of the organization, or an established rating system such as the Hazard Potential Classification of a dam. Adaptation actions could be recommended for higher rated risks if the industry is aligned on risk rating levels.

b. Develop a guideline or standard for climate risk assessments to help guide decision-makers in prioritizing climate and non-climate related risks to dam safety and operations in support of climate risk assessment guidance suggested in Section 2a. Dam infrastructure and operations, the watershed and other infrastructure on the river system should be assessed as a system to appropriately evaluate the climate risks against other priorities. This may include guidance on decision making under uncertainty that comes with climate data and risk.

4. Develop a process to support adaptation decision-making in consultation with stakeholders and researchers who have worked on climate adaptation specific to dams. The process should consider the ability of specific organizations to develop adaptation actions based on their unique needs, resources, and capabilities. It could include a set of existing adaptation measures or solutions that have been applied in Canada and, if available, how successful they were. This could help contribute to the resilience of dams in Canada by guiding owners and practitioners to evaluate all aspects of the dam system, operations, and the organization to ensure that these are aligned in adaptation planning.

5. Conduct further research on the climate change related impacts to small dams and prepare, as needed, a separate guidance document on climate adaptation considerations specific to small or lower consequence dams. Smaller dams might be impacted differently due to less stringent design parameter return periods, lower consequences, fewer resources and sometimes more labour intensive operations, which could lead to less or greater climate risk. This potential risk should be studied further in consultation with smaller dam owners across the country to determine how and if climate adaptation should be conducted for this application.

The involvement of stakeholders will be key in the implementation of the recommended actions including:

- Scientists, researchers, and communication experts,
- Standard development organizations,
- Regulators,
- Industry interest groups (CDA, ICOLD, etc.),
- Engineers and dam specialists, and
- Dam owners.

Other stakeholders would need to be consulted throughout the development process, such as First Nations communities, and specific focus groups could be required for certain topics, such as for small dams. The involvement of stakeholders and representation from across the country will help ensure that guidance documents provide methodologies that are feasible, adaptable, and relevant to the Canadian context.

An additional area warranting further study is the impact of climate change on integrated watershed management for river systems with multiple dams and dam owners with respect to flood management, environmental watershed requirements and regulated operating bands, as discussed in Section 4.3.

6 Conclusions

The objectives of this research were to assess to what extent water dams in Canada may be vulnerable to a changing climate, to identify best practices in climate change adaptation for dams, and discuss the need or opportunity for climate adaptation solutions including standards, guidelines, research, or other methods.

It was identified in the literature review that there are several ways in which dams in Canada could be vulnerable to climate change, and these vary significantly based on location. Their varying sizes, designs, and functions also play a role in how climate change may or may not impact them. Changes in precipitation and temperature were the biggest drivers for change. Associated potential impacts include increased floods, droughts, wildfires, winter flooding, ice storms, permafrost melting, debris and ice jams, and several others.

Dam owners and practitioners across the country were found to be engaged at varying levels in the topic of climate change. Some larger dam owners have staff trained in climate science and have performed site-specific vulnerability assessments to understand climate risk of their dam and apply adaptation measures if needed. However, some organizations are not prepared to prioritize climate risks until it becomes more clear or certain that their assets could be impacted. A major theme identified in this research is the uncertainty in the availability and the interpretation of climate change data, and therefore how to apply this information to assess climate risks and inform decision-making. Most dam owners and engineers are not trained specifically in climate science or risk-based decision-making. So, there is an opportunity for improvement.

The current availability of climate change data and the lack of a common understanding on how to interpret it are barriers that should be addressed in order to inform future guidelines and standards. Similarly, a system-wide understanding of risks to an asset would be needed to ensure that climate and non-climate related risks are appropriately prioritized in order to have climate change risk and corresponding mitigation actions incorporated into capital and operational planning for dams.

Some dam owners have applied climate risk assessment tools to understand the potential vulnerabilities of their assets to climate change, ranging from qualitative workshops to site-specific assessments of climate projections and impacts to a dam system. Generally, a demand for guidance comes from dam owners who have not yet assessed climate change risks, although barriers exist to implementing climate adaptation practices across the country.

The findings of this research demonstrate a need for a standard or guideline that provides a methodology for interpreting climate data to a site or watershed-specific setting; the application of this data to determine impacts to a dam system; the risk assessment associated with these potential impacts; and the identification of valuable adaptation actions or tools to respond to climate risk. Research and consultation would be needed to determine the appropriate level of detail to ensure feasibility and applicability to the various types of dams across the country while maintaining repeatable and thorough results. Further study is needed to determine the impacts climate change may have on small dams as climate risks, resources, and thus climate adaptation best practices will differ from those of large dams. Climate adaptation best practices compiled in a standard or guideline would benefit Canadian dam owners as well as practitioners since it could unveil unknown risks and tools for appropriate adaptation to climate change.

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Appendix A – Appendix A – Stakeholder Interviews

Interview Questions

Some or all of the general questions below were asked to all participants, as time allowed. Additional questions were asked based on the interviewee's background and area of expertise and the discussion in the interview.

1. Based on your experience, knowledge, and background to date, how is climate change impacting dam safety and operations? How would you expect this to change with further changes in our climate? In your perspective, what are the greatest climate change risks for dams in Canada?

2. How do you believe climate change should be considered in relation to the safety, operation, design, and maintenance of dams? (e.g. best practices, guidance, literature, standards, requirements, maintenance and operation procedures, operation management plans, asset management plans, future planned expenditure, risk assessments, financial planning, policy.)

   2.1 What do you believe could be the most effective method to encourage implementation of climate adaptation considerations for dams? (i.e. encourage academic and private research, support public literature, data platforms, funding programs, conferences and knowledge exchange, committees or taskforces, rules and regulations, codes, standards, guidance, by-law and laws, nothing, etc.)

3. Can you share any notable examples of climate adaptation and resilience of dams in Canada or internationally that have, in your opinion, been successful? (e.g. site-specific adaptations, organizational changes, wide-scale initiatives)

4. Have you noticed any trends or changes in the regulations, policy, operations management, design, best practices, discussions, general interest, etc. regarding dams' adaptation to climate change?

5. What are the barriers to considering climate change in relation to the safety, operation, design, and maintenance of dams? (e.g. lack of available literature, guidance, time, funding, motivation, expertise or knowledge.)

6. What are some resources that you have either come across or used to address climate risk or adaptation? (e.g. partners, tools, etc.)

7. Do you believe standards are needed to address climate adaptation for dams? If so, what would be an ideal format (standards, guidelines, regulations), and how, if at all, do you think these should be enforced?

   7.1. What is your perspective regarding the variation between provincial and territorial regulations across Canada and how this relates to climate change adaptation? What changes, if any, do you think would support safe implementation of climate change adaptation practices for dams in Canada?

   7.2. If you believe a standard is necessary, what scope (federal, provincial, organization-level) should it have?

CSA Group Research

In order to encourage the use of consensus-based standards solutions to promote safety and encourage innovation, CSA Group supports and conducts research in areas that address new or emerging industries, as well as topics and issues that impact a broad base of current and potential stakeholders. The output of our research programs will support the development of future standards solutions, provide interim guidance to industries on the development and adoption of new technologies, and help to demonstrate our on-going commitment to building a better, safer, more sustainable world.

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