NRC·CNRC CONSTRUCTION

Adaptation of Dams to Climate Change

Gap Analysis

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Climate Resilient Dams

Gap Analysis

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Executive Summary

Recognizing the need to adapt our new and existing infrastructure and operation procedures to withstand increased climatic loads and degradation mechanisms, the National Research Council Canada (NRC) has been collaborating with Infrastructure Canada to develop and revise codes, specifications, guidelines and assessment tools to advance adaptation solutions for Canadian infrastructure since 2016. Phase 1 of the Climate Resilient Buildings and Core Public Infrastructure (CRBCPI) initiative was undertaken at the NRC between 2016 and 2021 to integrate climate resilience into building and infrastructure design, guides, standards and codes. The target infrastructure types for the CRBCPI initiative included buildings, bridges, roads, rail, transit, and water and wastewater systems. In 2021, the NRC received approval to proceed with Phase 2 of the initiative, the Climate Resilient Built Environment (CRBE). In addition to the previously mentioned infrastructure types, dams are included in the scope of the CRBE initiative.

Dams retain enormous amounts of water and are designed to resist hydraulic loads, therefore, it is expected that factors related to climate change that affect water flow will also affect dams. Unexpected interruptions in dam operations may lead to significant economic loss, while dam failures may be catastrophic. Historically, dam design, construction and operation have been carried out assuming stationary climatic and non-climatic conditions. In today's changing climate, the assumptions of stationary climatic baselines may no longer be appropriate for long-term dam design and operations. The CRBE's Climate Resilient Dams (CRD) theme will focus on the development of technologies, procedures and guidelines for the adaptation of publicly-owned water dams to mitigate the adverse effects of a changing climate. It should be noted that tailing and mining dams are not included in the scope of the CRD project.

Water dams in Canada are owned by various entities such as federal and provincial governments, utilities and municipalities, agricultural districts, private organizations, and individuals. Canada does not have a federal regulatory agency or a unified program to guide the development of requirements for the safe management of dams. None of the provinces and territories had any specific legislation on dam safety until 1978 when the Province of Alberta established the first dam safety regulatory program in response to concerns due to a number of dam failures around the world. The main purpose of current dam safety regulations is to ensure that dams and their appurtenant and hydraulic structures are designed, constructed, maintained, operated and decommissioned with the best available technology and best practices. It should be noted that none of the dam safety regulations reviewed within the scope of this project took into consideration or directly mentioned climate change. In order to address this gap, the objectives of this project are: (1) to identify knowledge gaps in the adaptation of Canadian dams to climate change; and (2) to develop future research directions for the NRC's Construction Research Centre in the areas of climatic data requirements, operations, water quality, monitoring, geotechnical/structural aspects and material durability.

The gaps presented in this report are identified through literature review, interviews, discussions and consultations with dam experts and professionals, as well as a review of the current regulations. The following gaps are identified as potential research directions:

- **Quantification of climate change uncertainty**: The uncertainty associated with future projections of climatic data can be significantly high, in particular for compound parameters that include multiple climate variables, such as ice formation and flood. Due to the uncertainty in climate projections, particularly in long-term planning horizons, it is challenging to quantify the impact of climate change on water resources infrastructure such as dams. The quantification of climate change uncertainty and the share of each source of uncertainty are identified as gaps that need to be studied further.
- **Tools to forecast inflows and outflows:** Dam operation planning relies heavily on the prediction of inflows and outflows, both of which are influenced by the changing climate. Access to a tool that could provide the operators with a robust inflow and outflow forecast, while accounting for the change in climate, could allow the consideration of long-term trends in short-term (i.e., daily) decision-making operations.
- **Operations optimization**: Changes in a dam's inflows and outflows result in different dam operations. Their maintenance schedule, water allocation, sediment washing schedule and turbine operation are all impacted. Quantifying these impacts based on the expected unit variation in precipitation and temperature will help minimize the risks associated with climate change. The main objective here is to produce various climatic scenarios (both on precipitation and temperature) through model simulation and combine them with a state-of-the-art multi-objective optimization model while accounting for various dam operation and water allocation requirements. This tool, combined with the inflow and outflow forecasting tool described above, could quantify the impact of climate change on various dam operational requirements while accounting for the uncertainties associated with the changing climate.
- **Guideline for managing ice and break-up events**: Most of Canada is considered a cold climate area, where reservoirs and lakes are expected to freeze annually, and yet no guidelines are available on how to manage dams during these events. A warming climate will increase the frequency of these freezing events. Therefore, quantifying the impact of icing and break-ups on various dam operations and the structural integrity of dams and providing general guidelines to dam owners and operators could help with the management of dams during these events.
- **Development of an integrated water quality model**: Climatic events that are expected to increase in frequency and intensity have varying impacts on dam reservoir water quality and the aquatic habitat within the dam. Notably, under specific circumstances, certain reservoir characteristics are highlighted as increasing the reservoir vulnerability to water quality issues. As for proposed future work, it is recommended that, based on a review of the literature, an appropriate dam reservoir should be selected for the development of an integrated water quality model. The developed model can be a useful tool for the assessment of climate change impacts on water quality in a dam reservoir under various future climatic scenarios. The model can be extended to other reservoirs based on the physical characteristics of reservoirs and characteristics of the watershed.
- **Structural stability and integrity of concrete dams**: Extensive research has been conducted to date on the impact of climate change on hydraulic structures. However, most studies only focused on the impact of climate change on the hydrological aspects of the

problem. It is worth noting that the effects of the changing climate have not been accounted for in the design of currently operated concrete dams. Thus, the impacts of increased temperature and intense rainfalls on the deterioration mechanisms (e.g., concrete swelling due to alkali-silica reactions) and, in turn, the stability and structural integrity of existing dam safety are still uncertain. Therefore, it is important to study adaptive and preventive solutions to alleviate the impact of climate change on the stability and integrity of concrete dams.

- **Evaluation of potential acceleration in deterioration of concrete dams and preventative measures**: Climate change is expected to lead to an increase in the deterioration of concrete infrastructure in Canada, but there has been little investigation dealing with the impact of climate change on concrete dams. The environmental conditions to which a concrete element incorporating alkali-silica reactive aggregates is exposed to play a major role in dictating the progression and manifestation of the reaction and its damages. Alkali-silica reactions, which are known to be a serious problem for Canadian concrete dams, are affected by high humidity and high temperature. Methods to evaluate damages associated with alkali-silica reactions need to be revisited. Preventive methods, such as the use of supplementary cementitious materials to replace part of the cement in concrete, also need to be assessed for existing and new concrete dams to take temperature rise into account. Importantly, the combined effects of other deterioration mechanisms (freeze-thaw cycles, carbonation, corrosion, etc.) that are environmentally dependent must be investigated further.
- **Satellite-based dam monitoring**: Dam health monitoring is an indispensable tool for ensuring dam safety and maintaining operational functions during the service life of the dam. Many dams are located in remote regions of Canada and are hardly accessible to traditional surveying crews in the winter. Satellite-based monitoring techniques may offer a solution to this problem, however, it is still too early to trust observations from space as the only source of data for measuring surface displacements. Therefore, extensive research should be conducted to verify the suitability of the application of InSAR technology in the practice of dam monitoring.
- **Risk assessment**: Managing the risk of failure is a necessary action during a dam's service life. However, existing risk assessment tools for dams do not incorporate elements of climate change, and they do not provide any specific guidance on which adaptations should be made based on the existing deficiencies or expected failure modes. It would be beneficial for dam owners and engineers to be able to predict failure modes based on the location of the dam since the impacts of climate change are expected to vary across Canada. It would also be beneficial to provide a framework or recommendations on which adaptations should be used to address each deficiency and each expected effect of climate change.
- **Corrosion of penstocks and steel gates:** It is unclear how climate change may impact the corrosion of the dam’s steel components, such as steel penstock and gates. The corrosion and defects of these elements could seriously affect the safe operation and use of a dam. As such, it will be important to determine how climate change could affect the steel components of a dam.

- **Structural stability and integrity of earthfill dams**: The main gaps identified pertaining to this topic are: (1) the increased risk of susceptibility to seismic liquefaction of dams due to changes of effective stress of the soil; (2) the need to develop advanced methods based on artificial intelligence algorithms to predict variations in groundwater levels under various climatic conditions, and to assess the susceptibility of current slopes to future changes in climate; and (3) the need to identify critical conditions that may occur during the life of new dams as a result of climate change. Future effects of climate change, such as overtopping or damage to spillways due to increased precipitation, need to be addressed before the construction of new dams and as part of a retrofit of, or rehabilitation program for, existing dams.

The gaps identified above will be further evaluated and expanded upon through a workshop with dam industry professionals to be held in the 2022/2023 fiscal year where gaps, future research directions and projects will be finalized.

1 Introduction

1.1 Background

Scientific consensus has established that climate change triggers extreme weather events as well as high-risk chronic events. Recognizing the need to adapt our existing infrastructure to withstand increasing climatic loads and mechanisms of degradation, the National Research Council Canada (NRC) has been collaborating with Infrastructure Canada since 2016 to develop and revise codes, specifications, guidelines and assessment tools to advance adaptation solutions for existing and new infrastructure. Phase 1 of the Climate Resilient Buildings and Core Public Infrastructure (CRBCPI) initiative was undertaken at the NRC between 2016 and 2021 to integrate climate resilience into building and infrastructure design, guides, standards and codes. The CRBCPI initiative focused on infrastructure including buildings, bridges, roads, rail/transit and water/wastewater systems. In 2021, the NRC received approval to proceed with Phase 2 of the CRBCPI initiative, namely, the Climate Resilient Built Environment (CRBE) initiative. In addition to the previously mentioned infrastructure types, dams are included in the scope of the CRBE initiative.

1.2 Scope

Dams retain enormous amounts of water and are designed to resist hydraulic loads, therefore, it is expected that factors related to climate change that affect water flow will also affect dams. Unexpected interruptions in dam operations may lead to significant economic loss while dam failures may be catastrophic. Historically, dam design, construction and operation have been carried out assuming stationary climatic and non-climatic conditions. In today's changing climate, the assumptions of stationary climatic baselines are no longer appropriate for long-term dam design and operation. The CRBE's Climate Resilient Dams (CRD) theme will focus on the development of technologies, procedures, guidelines and standards in order to adapt publicly owned water dams to the changing climate. Currently, tailing and mining dams are not included in the scope of the CRD theme.

1.3 Objectives

It is anticipated that the CRD theme will last throughout the CRBE initiative (approximately five years including the 2021/2022 fiscal year). The objectives of this initial project under the CRD theme are:

- Identification of the impacts of climate change on existing dam management (i.e., operation and maintenance) and new dam designs;
- Understanding how to adapt new and existing dams to climate change by completing a gap analysis in areas including climate data needs and utilization of climate projections, dam operations, monitoring of changes in structural behaviour, and aspects of material durability as well as structural and geotechnical stability;

- Prioritization of research areas to fill the knowledge gaps related to climate change impacts on dam design and management;

- Stakeholder engagement with dam owners and operators as well as governing and organizing bodies such as the Canadian Dam Association (CDA); and

- Development of initial research project plans to be executed under the CRD theme for the remaining years of the CRBE project.

2 Dams and Appurtenant Hydraulic Structures

2.1 Definition of a Dam

According to the Canadian Dam Association (CDA), a dam is defined as a barrier constructed for the retention of water, water containing any other substance, fluid waste or tailings, provided the barrier is capable of impounding at least 30,000 m^3 of liquid and is at least 2.5 m high (Figure 2.1). In the case of a barrier across a stream or watercourse, height is measured vertically to the top of the barrier from the natural bed of the stream or watercourse at the downstream toe of the barrier.

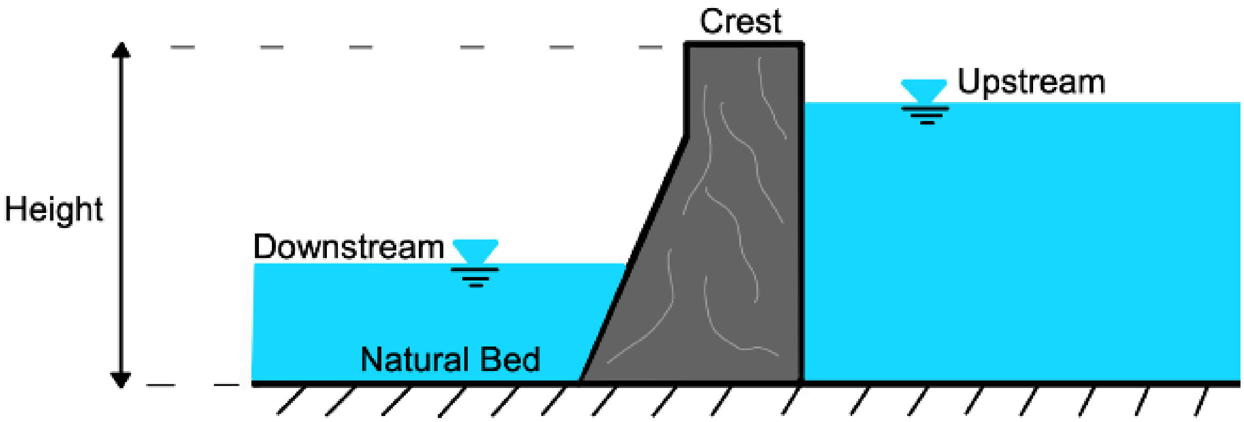

Figure 2.1 Dam for water retention on a stream/watercourse

The term ‘large’ dam, as per the International Commission on Large Dams (ICOLD), refers to dams that are 15 m or more in height measured from the lowest foundation to the crest, or dams that are between 5 to 15 m in height that impound more than 3 million m^3 of water (ICOLD, 2011).

2.2 Types of Dams

Many types of dams exist that use different materials and methods of resisting hydrostatic forces. Dam types can be divided into two major groups: embankment dams and concrete dams. This section briefly discusses these dam types.

2.2.1 Embankment Dams

Embankment dams, which can be constructed as earthfill or rockfill dams, are the most common type of dam worldwide due to their versatility, low cost, fast construction time and durability (Figure 2.2). Embankment dams can be constructed in both wide valleys and steep-sided gorges, and designs can be adapted to a wide range of foundation conditions due to their ability to accommodate significant settlement deformation without the risk of cracking.

(a) WAC Bennett hydroelectric dam – an earthfill dam in B.C. (iStock.com/rlesyk)

(b) Shuibuya Dam – a rockfill dam in China (iStock.com/xenotar)

Figure 2.2 Embankment dam examples

Embankment dams also present some risks and disadvantages since they are more susceptible to overtopping damage (Novak et al., 2004). If the reservoir level exceeds the height of the dam, erosion begins and is almost impossible to stop, ultimately leading to the failure of the dam. Embankment dams are also prone to seepage leading to internal erosion within the dam or foundation (Novak et al., 2004). If left uncontrolled, this seepage can progressively erode the embankment, beginning at the downstream face of the dam and moving towards the upstream face; this is known as piping. Similar to dam overtopping, once piping has fully developed it is almost impossible to stop and will most likely lead to the collapse of the dam. Additionally, seepage can also weaken the dam by saturating the embankment or by increasing pore-water pressures in the embankment.

2.2.2 Concrete Dams

Concrete dams are mostly constructed as gravity dams, buttress dams, arch dams or as a combination of these (Figure 2.3). Concrete dams are fit for locations with solid bedrock foundations. Gravity dams are typically used in vast valleys, although they may also be built in small canyons, especially if they are engineered as arch-gravity dams. Substantial discontinuities or stratifications in the rock foundation, as well as their direction, should be carefully evaluated to see if they favour sliding instability. Buttress dams can be constructed in comparable locations to gravity dams, however, they demand stronger rock to withstand greater local contact stresses at the buttress-rock interfaces. Arch dams are particularly equipped for narrow, steep-sided valleys if the rock foundations are practically non-deformable, especially at the abutments.

When substantial flood discharge is required or flood projections are very uncertain, concrete dams are preferred. Spillways, unlike embankment dams, may be built immediately at the dam crest, which makes them less prone to overtopping damage during high floods (Rattue, 2021).

(a) Revelstoke Dam – a gravity dam in B.C. (iStock.com/James_Gabbert)

(b) Roselend Dam – a buttress dam in France (iStock.com/sanddebeautheil)

(c) Stone Arch Dam – an arch dam in Ontario (iStock.com/LynMc42k)

Figure 2.3 Types of concrete dams: (a) gravity, (b) buttress and (c) arch dams

2.3 Appurtenant Hydraulic Structures

2.3.1 Spillways

Spillways are used to control the reservoir water level by providing safe passage of water over or around the dam from the reservoir to the downstream side. Spillways are normally used to pass flood waters from the reservoir to downstream and their design depends on the design flood, the type of dam, the dam location and the size of the reservoir. The design flood is one of the most important factors in the design of spillways. The design flood should be the probable maximum flood, which is the flood hydrograph that is forecasted using a combination of probable maximum precipitation, snowmelt and the worst flood-producing catchment conditions (Novak et al., 2004).

Per the definition of the CDA, the spillway types are classified by control mode: free, gated and combined spillways (CDA, 2019). The limited data from the CDA demonstrates that free spillways are the most popular type and are used in 24% of large dams in Canada. Gated spillways are less common and used in 14% of large dams in Canada. Finally, combined spillways incorporating controlled and uncontrolled elements are used in 7% of large dams in Canada (CDA, 2019). Although the available spillway data are classified according to the mode of control, the discussion that follows will focus on spillway types according to hydraulic criteria.

Concrete dams typically employ ogee spillways (Figure 2.4a), while embankment dams incorporate chute (Figure 2.4b) or shaft (Figure 2.4c) spillways. Although mostly used in ancient times, stepped spillways (Figure 2.4d) regained popularity with the emergence of new dam construction methods, in particular, roller compacted concrete (RCC) dams (Novak et al., 2004).

(a) Ogee spillway of the Cleveland dam in B.C. (iStock.com/AlbertPego)

(b) Chute spillway of a dam in northern Mauricie, Québec (iStock.com/Gabalex)

(c) Shaft spillway of the Monticello dam, USA (iStock.com/fusaromike)

(d) Stepped spillway of the Wimbleball dam in Somerset, UK (iStock.com/Tom Meaker)

Figure 2.4 Examples for spillway types

2.3.2 Energy Dissipation Structures

Another important element for dams is energy dissipation devices. The water discharged through the dam spillway contains massive amounts of energy, which may cause erosion downstream, leading to structural instability and failure of the dam and spillway. The energy of the water flowing in the spillway can be dissipated in five phases (Figure 2.5): (1) on the spillway surface; (2) in a freefalling jet; (3) at impact in the downstream pool; (4) in the stilling basin; and (5) at the outflow into the river (Novak et al., 2004). A spillway may use a single phase or a combination of phases for energy dissipation.

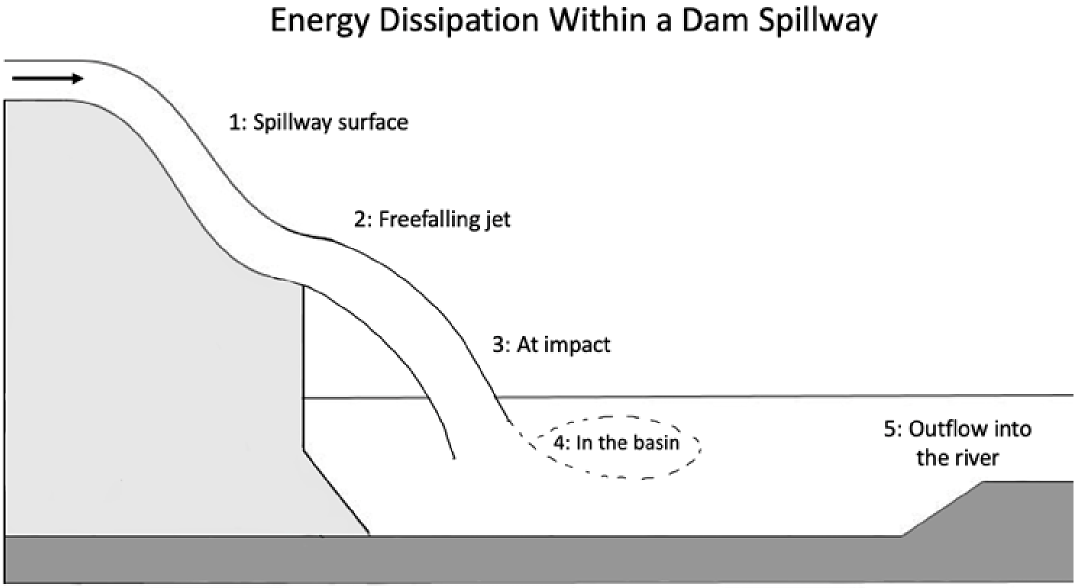

Figure 2.5 The five phases of energy dissipation in a dam spillway
(adapted from Novak et al. (2004))

2.3.3 Gates and Valves

Gates and valves are used in every hydraulic scheme and they serve to open and close the water-conveying structures of the dam. Gates and valves can be divided into two categories according to the position of the opening in relation to the level of headwater: (1) crest gates and (2) submerged gates and valves. Unlike crest gates, submerged gates operate under high pressure. Steel gates and valves are the most widely used for all types of dams due to their high strength and ease of fitting and erection. Aluminum alloy gates and valves are also installed for some dams because they are light and resistant to corrosion. The application of reinforced concrete gates is very limited due to the large mass of these gates (Tanchev, 2014).

Figure 2.6 Water rushing through gates at the Kananaskis Dam in Alberta
(iStock.com/Androsov)

2.3.4 Penstocks

Penstocks are closed pipes that convey water from the intake to the turbine, and most hydroelectric dams include some type of penstock (Figure 2.7). The length of the penstock can range from a few feet to several hundred feet and they can be installed above or below ground (ASCE, 2018). Penstocks can be made of steel, reinforced concrete, prestressed concrete or fibre-reinforced polymer. Steel penstocks are considered high-pressure conduits that are usually large in diameter and, during normal conditions, can operate with frequent surges (AISI, 1998).

(a) Penstocks of the Canyon Dam in Revelstoke, B.C. (iStock.com/SeanFerguson)

(b) Close-up of penstocks at Snoqualmie power station (iStock.com/Joecho-16)

Figure 2.7 Penstocks in hydroelectric dams

2.4 References

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3 Dam Inventory of Canada

3.1 Dams per Province and Territory

3.1.1 General Distribution

It is believed that more than 16,000 publically and privately owned dams, including tailing and mining dams, exist in Canada. Table 3.1 presents the number of dams in Canada per province, territory and federal authority based on the Canadian Dam Association (CDA) database (CDA, 2019b). Approximately 38% of dams in Canada are managed by Quebec authorities and approximately 20% and 12% of dams are managed by Ontario and British Columbia authorities, respectively. Five provinces, namely Ontario, Quebec, British Columbia, Alberta and Saskatchewan, manage 87% of the dams in Canada. Figure 3.1 is a pie chart illustrating the distribution of dams in Canada.

Table 3.1 Distribution of dams in Canada per province, territory and federal authority according to the CDA

Province/Territory	Abbreviation	Number of Dams	Percentage of Total
Ontario	ON	3,300	20%
Quebec	QC	6,200	38%
Nova Scotia	NS	200	1%
New Brunswick	NB	240	1%
Manitoba	MB	570	3%
British Columbia	BC	1,932	12%
Prince Edward Island	PE	N/A	N/A
Saskatchewan	SK	1,315	8%
Alberta	AB	1,506	9%
Newfoundland and Labrador	NL	700	4%
Northwest Territories	NT	100	1%
Yukon	YT	21	0.1%
Nunavut	NU	Unknown	Unknown
Canadian Federal Government	FG	325	2%
Total		**16,409**	

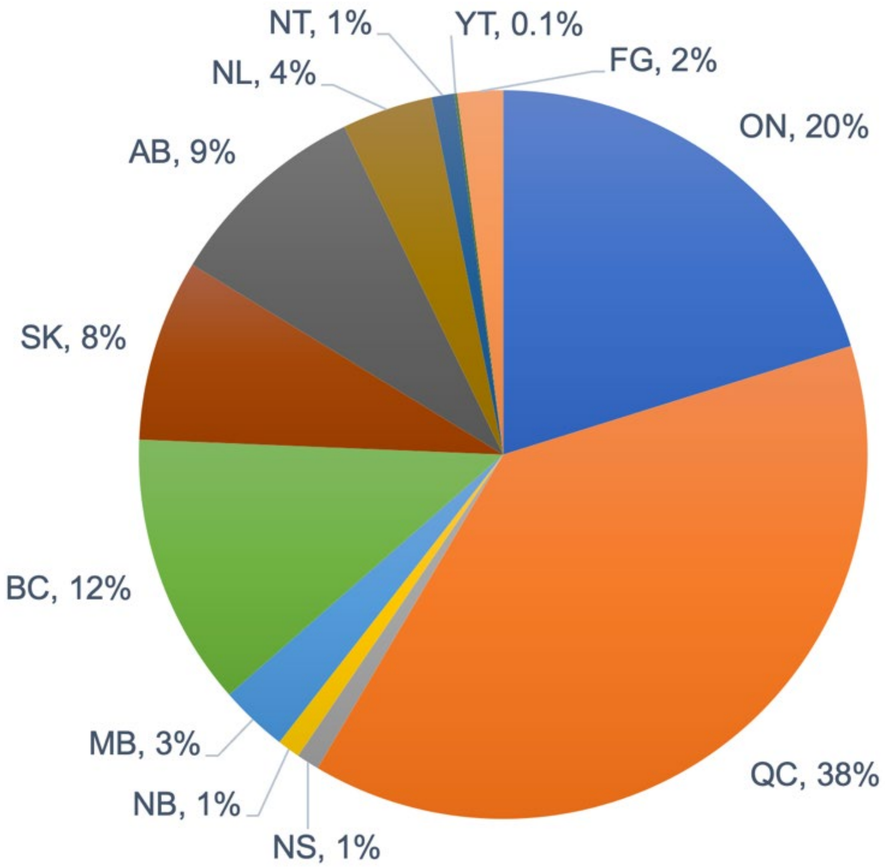

Figure 3.1 Distribution of dams in Canada per province, territory and federal authority

In order to create an information database for Canadian dams, communication was established with provincial and territorial ministries. Reasonable attempts, within the scope and budget of the project, were made to collect information on the dams from each region including dam function (e.g., power generation, irrigation, etc.), height, operation date (i.e., active since) and type (e.g., earthfill, concrete gravity, etc.). Only Quebec and British Columbia provided all of the information requested, resulting in well-established databases for those two provinces. Although information was obtained from most of the other provinces, a complete database could not be established. No database could be established for the dams managed by the territories. The next sections outline some of the features of the dams from Quebec, British Columbia and Alberta.

3.1.2 Dams in Quebec

There are 8,235 water-retaining structures documented by the province of Quebec. However, only 5,706 of these are defined as dams since they satisfy the height requirement of 2.5 m or greater as outlined by the CDA. As such, only those dams are considered in this section. Figure 3.2 is a pie chart illustrating the distribution of dams in Quebec categorized by purpose. Recreational and resort dams are the most common at 45% and hydroelectric dams are the second-most common at 22%. Dam categories that make up below 1% of the total have been removed for clarity.

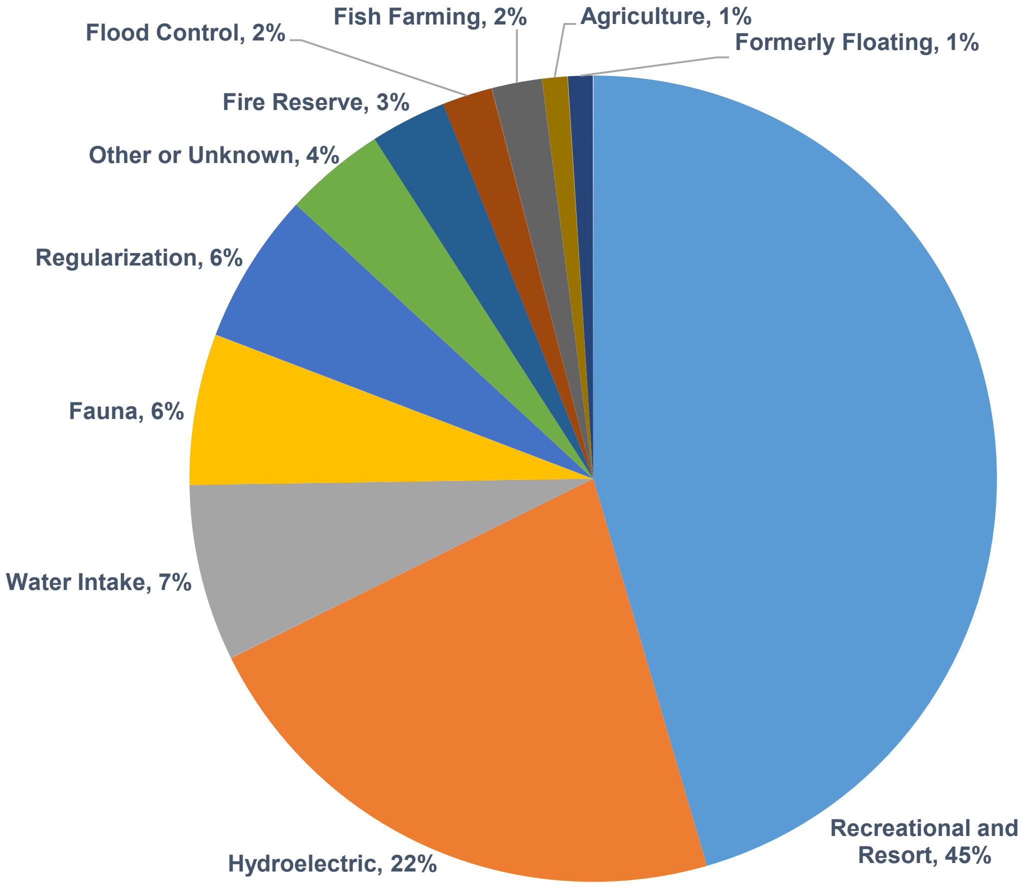

Figure 3.2 Distribution of dams in Quebec categorized by purpose

Figure 3.3 is a pie chart illustrating the distribution of dams in Quebec categorized by type. Earthfill dams are the most common at 43% and concrete-gravity dams are the second-most common at 31%.

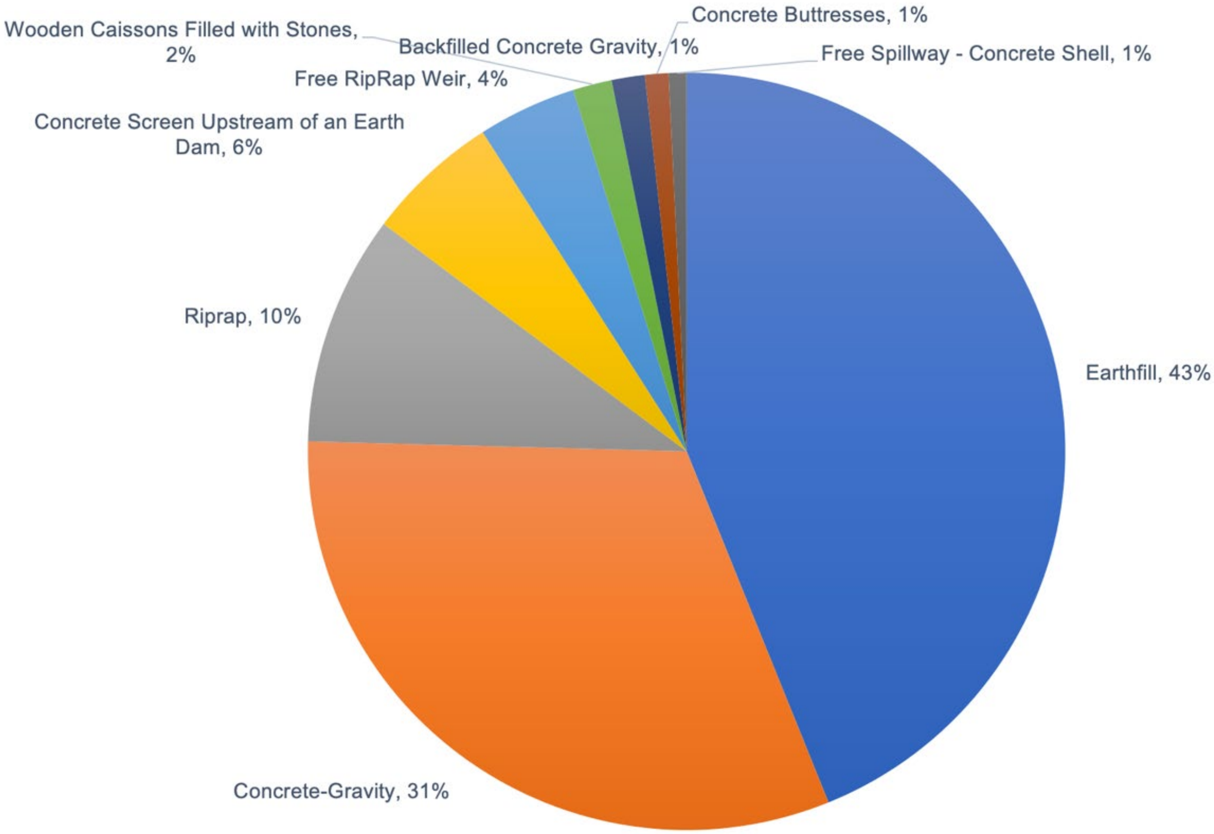

Figure 3.3 Distribution of dams in Quebec categorized by type

3.1.3 Dams in British Columbia

There are 2,544 dams documented by the province of British Columbia. As illustrated in Figure 3.4, embankment (earthfill/rockfill) dams are the most common making up 80% of the dams in British Columbia followed by concrete dams, which make up 11%. Note that dam types below 1% were removed and certain dam types were combined for clarity (e.g., Free Spillway – Concrete Shell).

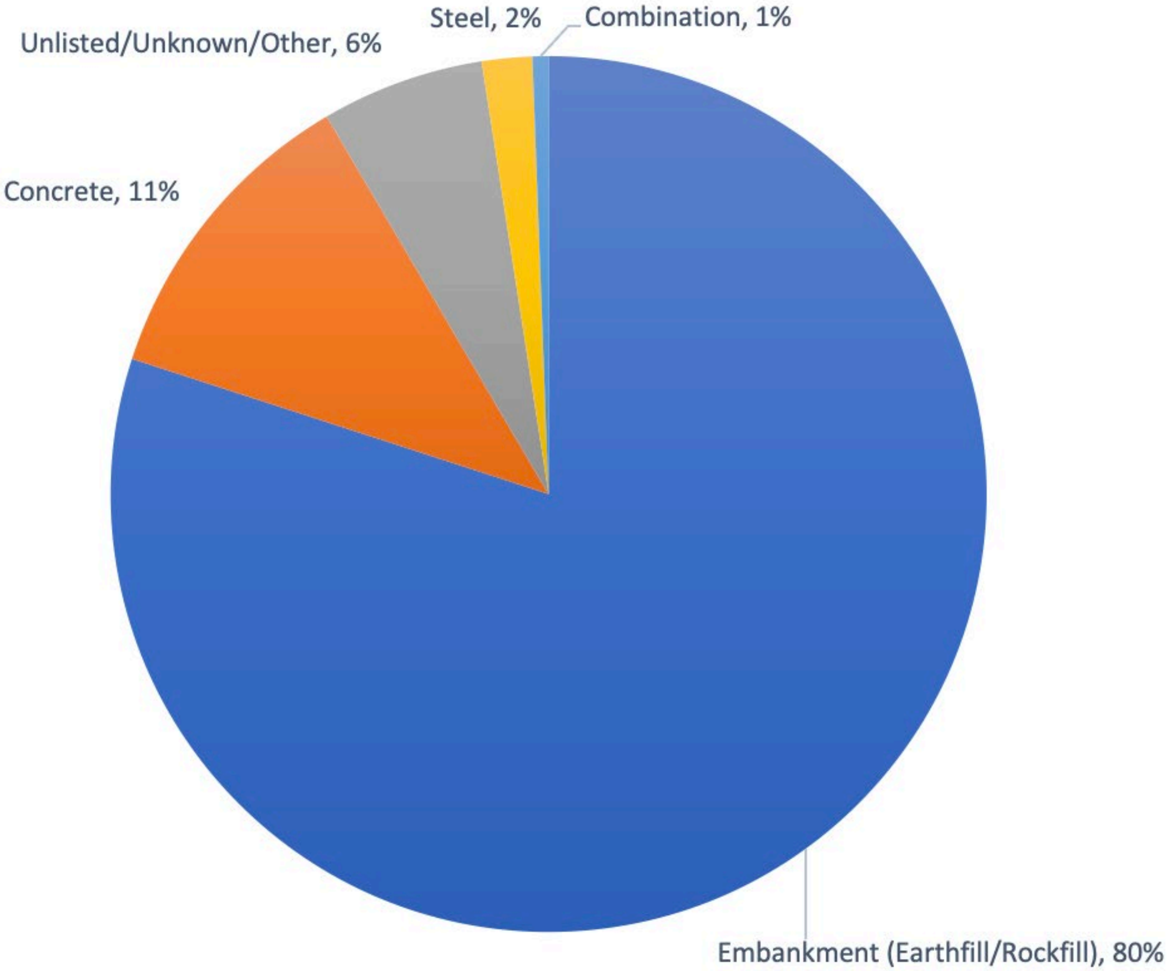

Figure 3.4 Distribution of dams in British Columbia categorized by type

3.1.4 Dams in Alberta

There are 1,277 dams documented by the province of Alberta. Figure 3.5 is a pie chart illustrating the distribution of dams in Alberta categorized by purpose. Many of the dams documented are used for multiple purposes. For example, a dam can be used for both recreation purposes and as a water supply and, therefore, adds to the total dam count for both categories. Categories that accounted for 1% or less were removed for clarity. For example, only 18 hydroelectric dams are documented in Alberta accounting for 1% of the total, therefore, hydroelectric dams are not shown in the figure. This is due to the fact that in Alberta, fossil fuels account for around 90% of the energy generated, with coal and natural gas accounting for 36% and 54%, respectively (CER, 2022). In contrast, renewable energy sources such as wind, hydroelectric and biomass account for the remaining 10% (CER, 2022), which explains why hydroelectric dams in Alberta only account for 1% of the total.

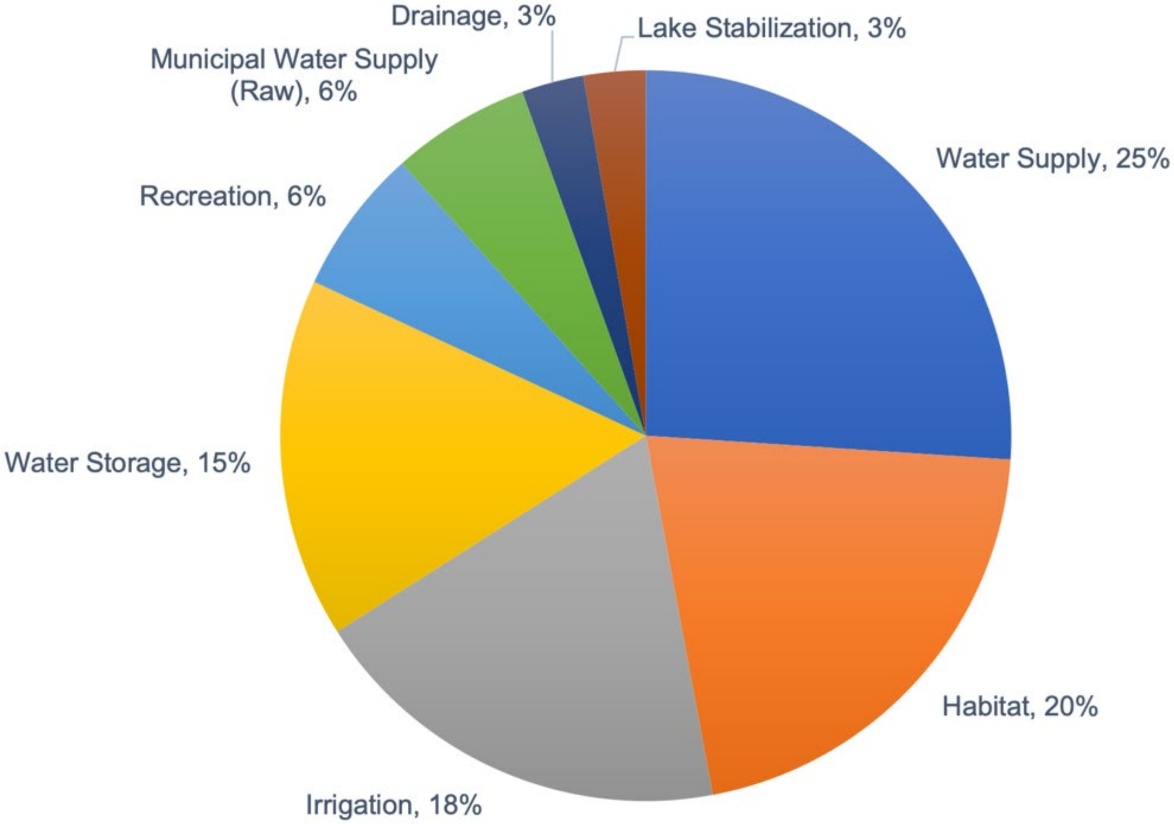

Figure 3.5 Distribution of dams in Alberta categorized by purpose

3.2 Large Dams

The International Commission on Large Dams (ICOLD) defines large dams as those with a height of 15 m or more from the lowest foundation to the crest, or those between 5 m and 15 m impounding more than 3 million m^3 of water (ICOLD, 2011). According to the CDA, there are 1,157 large dams in Canada; which make up about 7% of the total number of dams in Canada (CDA, 2019b). Table 3.2 presents the distribution of these dams and Figure 3.6 is a pie chart illustrating this distribution. Based on this information, Quebec houses 56.3% of the large dams in Canada, while Ontario has the second-highest percentage of large dams with 10.2%.

Table 3.2 Distribution of large dams in Canada per province and territory according to the CDA

Province/Territory	**Abbreviation**	**Number of Large Dams**	**Percentage of Total**
Ontario	ON	119*	10.2%
Quebec	QC	652*	56.3%
Nova Scotia	NS	36	3.1%
New Brunswick	NB	16	1.4%
Manitoba	MB	40	3.5%
British Columbia	BC	95	8.2%
Prince Edward Island	PE	0	0%
Saskatchewan	SK	52	4.5%
Alberta	AB	57	4.9%
Newfoundland and Labrador	NL	85	7.3%
Northwest Territories	NT	3	0.3%
Yukon	YT	4	0.3%
Nunavut	NU	-	-
Total		**1,157**	**100%**

*Two dams are shared by Quebec and Ontario and are counted for both provinces, therefore, if the number of dams in the table are added together, the outcome will be 1,159, which is two more than the actual number of dams (1,157).

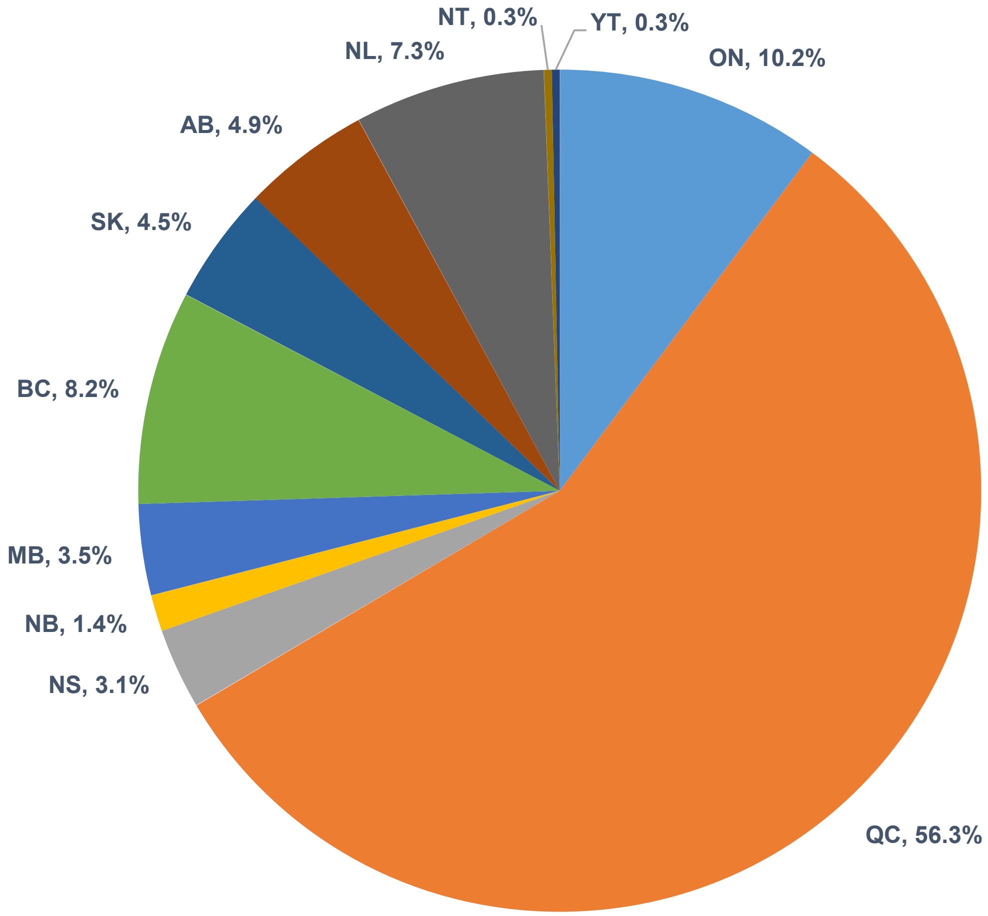

Figure 3.6 Distribution of large dams per province and territory (provinces and territories with less than 1% have been omitted from the figure)

Table 3.3 presents the distribution of large dams in Canada categorized by purpose and Figure 3.7 is a pie chart illustrating this distribution. The most common category of large dams is hydroelectric making up 70% of the total number of dams; which is not surprising considering that Canada is the fourth-largest producer of hydroelectricity in the world (International Hydropower Association, 2021). The second-largest category of large dams is recreation making up 10% of the total number of dams. This is closely followed by water supply, which makes up 9%, while the other categories have less than one hundred dams each.

Table 3.3 Distribution of large dams in Canada categorized by purpose

Purpose	Abbreviation*	Number of dams	Percentage of total
Flood Control, Flood Mitigation	C	85	7%
Irrigation	I	74	6%
Hydroelectric	H	865	70%
Fish farming	F	2	0.2%
Navigation	N	16	1%
Recreation	R	127	10%
Water supply	S	114	9%
Other unlisted	X	33	3%
Total		1,316**	

*Abbreviations are the same as the reference document (CDA, 2019a).

**The total number of dams is greater than 1,157 (see Table 3.2) since some dams are used for multiple purposes.

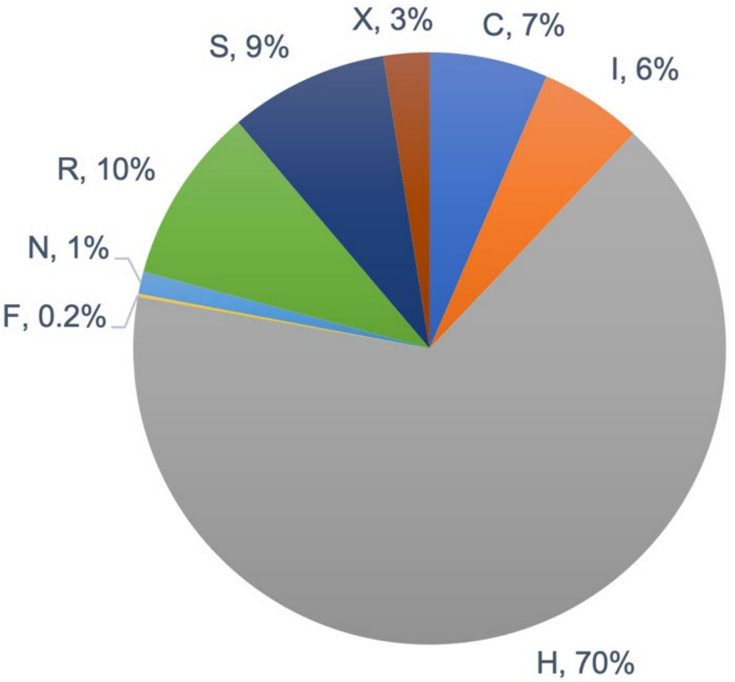

Figure 3.7 Distribution of large dams in Canada categorized by purpose (abbreviations are defined in Table 3.3)

Table 3.4 presents the distribution of large dams in Canada categorized by type and Figure 3.8 is a pie chart illustrating this distribution. Earthfill/rockfill dams are the most common type making up 64% of the total number of dams, followed by gravity dams, which make up 31%.

Table 3.4 Distribution of large dams in Canada categorized by type

Type of Dam	Abbreviation	Number of Dams*	Percentage of total
Earthfill/Rockfill	ER	848	64%
Buttress	CB	15	1%
Arch/Multiple Arch	AR	12	1%
Gravity (masonry or concrete)	PG	408	31%
Unlisted	XX	34	3%

*The total number of dams is greater than 1157 (see Table 3.2) since some dams are made using more than one type.

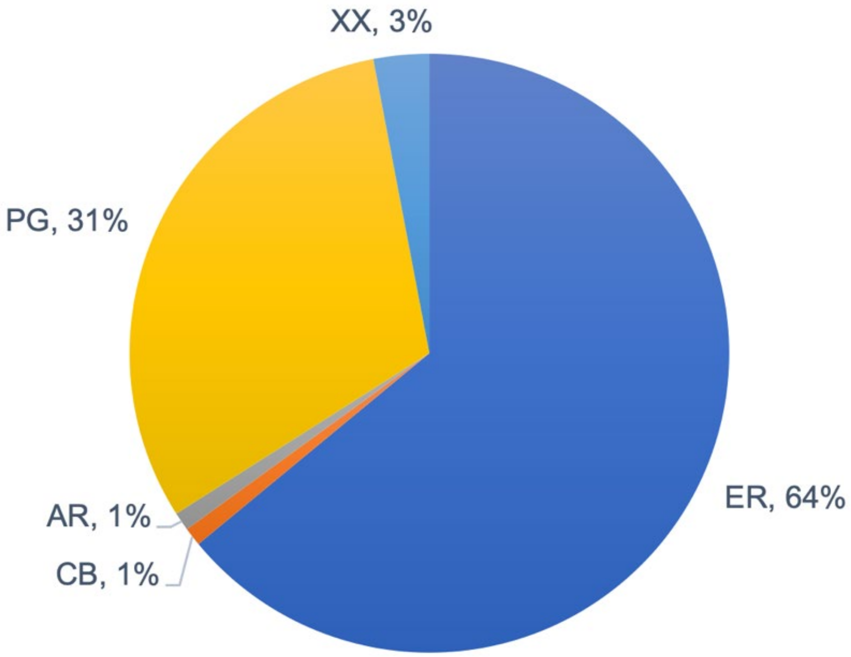

Figure 3.8 Distribution of large dams in Canada categorized by type (abbreviations are defined in Table 3.4)

3.3 Outcomes

Based on the information above, some of the outcomes are as follows:

- There are over 16,000 dams in Canada. Quebec entities operate 38% of these dams, followed by Ontario with 20% and British Columbia with 12%. Canadian Federal Government entities are responsible for 2% of the dams in Canada;
- Ontario, Quebec, British Columbia, Alberta and Saskatchewan hold almost 90% of the dams in Canada;
- Most provinces and territories do not keep an up-to-date, complete and comprehensive database of their dams that is also easily accessible to the public;

- Approximately 7% (or 1,157) of the more than 16,000 dams in Canada fit ICOLD's definition of 'large' dams;
- The most common purposes of large dams in Canada are hydroelectric at 70%, recreation at 10% and water supply at 9%; and
- The most common types of dams in Canada are embankment (earthfill/rockfill) dams. For large dams, embankment dams constitute 64% of the dams in Canada, followed by concrete gravity dams at 31%.

3.4 References

CDA (Canadian Dam Association). (2019a). Dams in Canada. Retrieved from: https://cda.ca/sites/default/uploads/files/Dams-In-Canada-2019%20-%20FINAL%20-%20revised%20-%20RESTRICTED.pdf

CDA (Canadian Dam Association). (2019b). Inventory of Large Dams in Canada. Retrieved from: https://cda.ca/sites/default/uploads/files/Inventory-registre-Canada-2019%20-%20FINAL%20-%20RESTRICTE.pdf

CER (Canada Energy Regulator). (2022). Provincial and Territorial Energy Profiles – Alberta. Retrieved from: https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/provincial-territorial-energy-profiles/provincial-territorial-energy-profiles-alberta.html

ICOLD (International Commission on Large Dams). (2011). Constitution. Retrieved from: https://www.icold-cigb.org/userfiles/files/CIGB/INSTITUTIONAL_FILES/Constitution2011.pdf

International Hydropower Association. (2021). Hydropower Status Report. Retrieved from: https://assets-global.website-files.com/5f749e4b9399c80b5e421384/60c2207c71746c499c0cd297_2021%20Hydropower%20Status%20Report%20-%20International%20Hydropower%20Association%20Reduced%20file%20size.pdf

4 Dam Regulatory Structure in Canada

4.1 Canadian Regulators

Dams in Canada are owned by various entities such as federal and provincial governments, utilities and municipalities, industrial and mining companies, agricultural districts, and even private individuals. Canada does not have a federal regulatory agency or a unified program to guide the development of requirements for the design and safe management of dams (CDA, 2020). Water management, construction, operation, maintenance and decommissioning of dams and the regulation of their safety are under the jurisdiction of the provincial and territorial governments in Canada. It is worth noting that the federal government has regulatory requirements for dams constructed on boundary waters with the USA or on navigable waters. The requirements also extend to dams constructed and operated by Canada's nuclear industry. Furthermore, federally owned dams are exempt from provincial regulations.

None of the provinces and territories had any specific legislation on the safety of dams until 1978 when the province of Alberta established the first dam safety regulatory program in response to concerns due to several dam failures around the world (Alberta Government, 2022). The main purpose of these dam safety regulatory systems is to ensure that dams and their appurtenant and hydraulic structures are designed, constructed, maintained, operated and decommissioned with the best available technology and best applicable practices (British Columbia, 2016; Ontario, 2020; Quebec, 2021; Alberta Government, 2022; Department of Environment and Climate Change (Newfoundland and Labrador), 2022; Department of Transportation and Infrastructure (Manitoba), 2022). The following dam safety regulations and acts were reviewed in this report and none of them considered or directly mentioned the impacts of climate change.

- Alberta Government. (2022). Dam and canal safety - Regulatory system. Retrieved from: https://www.alberta.ca/dam-and-canal-safety-regulatory-system.aspx
- British Columbia. (2016). Dam Safety Regulation (under the Water Sustainability Act). B.C. Reg. 40/2016.
- Ontario. (2020). Construction (under the Lakes and Rivers Improvement Act). O. Reg. 454/96.
- Quebec. (2021). Dam Safety Act. CQLR S-3.1.01.
- Department of Environment and Climate Change (Newfoundland and Labrador). (2022). Dam Safety Program. Retrieved from: https://www.gov.nl.ca/ecc/waterres/damsafety/#operations
- Department of Transportation and Infrastructure (Manitoba). (2022). Water Management Engineering and Construction. Retrieved from: https://www.gov.mb.ca/mit/wms/wmec/index.html

Furthermore, the following provincial acts and regulations were reviewed and none of them considered or directly mentioned the impacts of climate change either.

- Alberta: Water Act and Dam and Canal Safety Directive
- British Columbia: Water Sustainability Act – Dam Safety Regulation
- Manitoba: The Water Rights Act
- New Brunswick: The Clean Water Act
- Newfoundland and Labrador: The Water Resources Act
- Nova Scotia: The Environment Act
- Ontario: The Lakes and Rivers Improvement Act
- Prince Edward Island: Has no legislation on dams.
- Quebec: Dam Safety Act – Dam Safety Regulation
- Saskatchewan: The Water Security Agency Act
- Northwest Territories: Mackenzie Valley Resource Management Act and The Waters Act
- Nunavut: Nunavut Waters and Nunavut Surface Rights Tribunal Act
- Yukon: The Waters Act

Various Canadian dam regulatory agencies and the link to their legislating and/or regulatory documents are listed in Table 4.1. Where possible, Table 4.1 also includes the approximate number of dams owned and regulated by these regulatory agencies. In addition to the aforementioned Canadian documents, US federal guidelines for dam safety were also reviewed (Interagency Committee on Dam Safety - FEMA, 1979-2004; FEMA, 2015) and it was concluded that they do not account for climate change either.

Formed and guided by the Boundary Waters Treaty between Canada and the USA, the International Joint Commission (IJC) controls the watersheds between the two nations. The IJC’s report on watersheds (IJC, 2017) examines the effects of climate change on the watersheds controlled by the IJC and proposes a basic framework and recommends techniques for resolving issues regarding watersheds that boards can adopt. The International Watersheds Initiative (IJC, 2017) provides some background on what we know about climate change (Section 2), discusses water management at the onset of climate change (Section 3), and outlines the board responsibilities regarding climate change (Section 4). The framework is provided in basic terms, while the framework's actual application (to be published in future) will demand more comprehensive development and piloting. This means that while the framework addresses climate change, it does not discuss its implications on dams specifically.

Table 4.1 Government dam regulatory organization, stakeholders, and associate regulations and guidelines (Canadian Dam Association, 2020)

Province/ Territory	Ministry/ Agency	Legislation/ Regulation	Regulation	Guidelines	Number of Dams
British Columbia, Water Supply Dams	Ministry of Forests Water Management Branch Dam Safety Program	Water Sustainability Act	Dam Safety Regulation	Inspection & Maintenance of Dams Plan Submission Requirements Downstream Consequence of Failure Classification Interpretation Guideline Compliance and Enforcement Policy Legislated Dam Safety Reviews in BC: APEGBC Guidelines Site Characterization for Dam Foundations in BC: APEGBC Guidelines	1,814 regulated dams
British Columbia, Mining Dams	Ministry of Energy, Mines and Low Carbon Innovation	Mines Act	Health, Safety and Reclamation Code	Dam Safety Inspections EGBC Professional Guidelines & Advisories Legislative Dam Safety Review in BC: APEGBC Guidelines	118
Alberta Non-Energy Related Dams (Water and Tailings Dams)	Alberta Environment and Parks: Dam and Canal Safety	Water Act	Water (Ministerial) Regulation	Dam and Canal Safety Directive	1,276 regulated dams
Alberta Energy Related Dams	Alberta Energy Regulator	Water Act	Water (Ministerial) Regulation	Dam and Canal Safety Directive	230 regulated dams
Saskatchewan (Water Supply Dams)	Water Security Agency	Water Security Agency Act	Water Security Agency Act	No	1,300
Saskatchewan Tailings Dams	Ministry of Environment	Environmental Assessment Act	No	No	15

* "No" means that no legislation, regulation or act is available.

** Several items in this table are hyperlinks. You may need to Ctrl + click to follow the link.

Table 4.1 (continued)

Province/ Territory	Ministry/ Agency	Legislation/ Regulation	Regulation	Guidelines	Number of Dams
Manitoba	Manitoba Conservation and Climate	The Water Rights Act	No	No	570
Ontario Water Supply Dams	Ministry of Natural Resources and Forestry	Lakes and Rivers Improvement Act (LRIA)	Ontario Regulation 454/96 Construction	LRIA Administrative Guide, Technical Bulletins and Best Management Practices	3,300
Ontario Tailings Dams	Ministry of Natural Resources and Forestry	Mining Act	No	No	N/A
Quebec (water Supply)	Ministère de l'Environnement et de la Lutte contre les changements climatiques	Dam Safety Act	Dam Safety Regulation	Guides, Forms and Maps	6,200
Quebec (Mining dams)	Natural Resources and Forests	Mining Act	No	No	N/A
New Brunswick	Environment & Local Government	Clean Water Act	No	No	240
Nova Scotia	Environment and Climate Change	Environment Act-Regulation	No	No	200
Newfoundland & Labrador	Department of Environment and Climate Change	Water Resources Act	No	No	700
Prince Edward Island	Environment, Energy and Climate Action	No	No	No	N/A

* “No” means that no legislation, regulation or act is available.

** Several cells in this table are hyperlinks. You may need to Ctrl + click to follow the link.

Table 4.1 (continued)

Province/ Territory	Ministry/ Agency	Legislation/ Regulation	Regulation	Guidelines	Number of Dams
Yukon Territory	Yukon Water Board: Water Resources Section	Waters Act	No	No	21
Northwest Territories	Mackenzie Valley Land and Water Board	Mackenzie Valley Resource Management Act Waters Act	Waters Regulations	No	100
Nunavut	Nunavut Water Board	Nunavut Waters and Nunavut Surface Rights Tribunal Act	No	No	Unknown
Canadian Federal Government	Canadian Nuclear Safety Commission	Nuclear Safety and Control Act	No	Various	100
Canadian Federal Government	Parks Canada	Internal Directive (self-regulated)	No	Various	225

* “No” means that no legislation, regulation or act is available.

** Several items in this table are hyperlinks. You may need to Ctrl + click to follow the link.

While the research in this section focuses on published work, it is important to note that the Canadian Standards Association (CSA) is currently developing the new standard CSA S910, “Climate Change Resiliency for Dams”. The National Research Council Canada is aware of this standard and is working with the CSA as part of its development.

4.2 International Organizations on Dams and Climate Change

Unlike many Canadian regulations, several international dam organizations such as the International Commission on Large Dams (ICOLD), the IJC, and the International Organization for Standardization (ISO) have discussed climate change and its impact on dam safety and management.

ICOLD’s Bulletin 169, titled Global Climate Change, Dams, Reservoirs and Related Water Resources (ICOLD, 2016), discusses the climate-induced impact and risk assessment on dams, reservoirs and water resources systems (Section 5). It then highlights climate as one of the drivers for change in the world’s water resources. The bulletin then outlines the greenhouse gas emissions associated with reservoirs and water resources (Section 8), presents six case studies on adaptation strategies from around the world (Section 9), and summarizes ICOLD’s recommendations (Section 10).

Section 5 of the bulletin describes various tools and approaches that dam and reservoir owners can use to assess the possible implications of climate change on their water resources systems. Subsection 5.1 examines recommendations by the Intergovernmental Panel on Climate Change (IPCC) for regional impact evaluations. Subsection 5.2 summarises the key reasons why dam and reservoir managers and designers should reconsider their activities taking climate change into consideration, and also describes the analysis process needed to assess the benefits of adaptation strategies. Subsection 5.3 discusses uncertainties and probabilistic techniques as well as different approaches typically used to conduct studies on the effects of climate change. Subsection 5.4 provides examples of impact studies and adaptation measures used to deal with the effects of climate change.

Section 9 of the bulletin reviews the principles of adapting to climate change and how these principles vary from country to country, region to region, and over time. The need to address climate change will drive how water is managed, regardless of priorities. Climate change affects hydrological, ecological, economic and sociocultural system interactions. Climate change management necessitates flexibility in water quantity, quality and predictability; steps to deal with exceptional environmental conditions, unprecedented economic and societal constraints; and efforts to ease social adjustment in the affected region. The adaptation principles as listed in ICOLD’s Bulletin are shared below:

(1) Projected impacts of climate change on water resources and floods and droughts are uncertain and cannot provide exact information on the rate of future changes to decision-makers, but they can offer very useful general information and could serve as a preliminary and initial assessment.

(2) Water availability and water quality are cornerstones of social and economic development and environmental sustainability.
(3) In the expanded context of the water resources system, dams and reservoirs become an integral part of a multifaceted adaptation strategy, not the single focus.
(4) Collaboration across multiple disciplines, interests, and stakeholders is necessary to provide coordinated and well-targeted water resources management.
(5) Adaptation to climate change will take more than a technological fix.
(6) The best plan for adaptation includes a commitment to commence its implementation.
(7) Public involvement, engagement and, ideally, support early in the decision-making process will also pave the way for constructive decision-making about adaptation priorities and the development of options and strategies.
(8) Planned (and coordinated) adaptive management aims to replace ad hoc responses with long-term (policy) arrangements, which may include interim contingency measures. This is particularly critical in the case of managing water supplies in times of extreme and prolonged drought.
(9) Human consumption practices that undermine the environment are, as such, unsustainable, in particular for arid and semi-arid regions where more frequent drought events are probable in the future due to climate change.
(10) The safest flood preparedness allows floods to “pass safely” rather than aiming for complete containment, as complete containment may not be achievable with climate change.
(11) Water must be of suitable quality for its intended purpose (ICOLD, 2016).

The bulletin also provides structural adaptation measures in Subsection 9.2.1. The following is a list of prospective structural measures, as listed in ICOLD’s Bulletin, that could be implemented in advance of or as part of climate change:

- Change the number and type of water control gates both for flood management and water release requirements.
- Increase in the capacity of the spillway works and/or the provision of emergency spillways.
- Add controllable gates to free overflow spillways in order to provide greater regulation of flood peaks.
- Modify the dimension of canals or tunnels that are for water transfer.
- Create new upstream storage reservoirs and re-consider the multi-purpose potential of new reservoir projects.
- Modify the active storage capacity of reservoirs by increasing the height of the storage dam and/or raising the sill level of the overflow works.
- Increase the amount of freeboard above the top water level to accommodate predicted increases in flood rise and wave surcharge values.
- Replace or reinforce upstream slope protection such as rip-rap to provide satisfactory erosion protection under increased dynamic loading from waves (ICOLD, 2016).

These structural changes will be applicable to a wide range of dam and reservoir projects. Most water resource managers and engineers will be highly familiar with these types of physical interventions, including the expected costs, technical problems, and potential advantages. On the other hand, the uncertainties related to initiatives associated with climate change will add to the level of uncertainty in all of these areas. One thing is certain: in the future there will be a greater need to adapt, adjust and change. To solve these problems, future dams must be ready for structural interventions, such as the addition of spillways or other physical components that can be added to the infrastructure later if necessary (ICOLD, 2016).

4.3 References

Alberta Government. (2022). Dam and canal safety - Regulatory system. Retrieved from: https://www.alberta.ca/dam-and-canal-safety-regulatory-system.aspx

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CSA Group. (2019). Climate Change Resiliency for Dams. Retrieved from: https://www.scc.ca/en/standards/notices-of-intent/csa/climate-change-resiliency-for-dams.

Department of Environment and Climate Change (Newfoundland and Labrador). (2022). Dam Safety Program. Retrieved from: https://www.gov.nl.ca/ecc/waterres/damsafety/#operations

Department of Transportation and Infrastructure (Manitoba). (2022). Water Management Engineering and Construction. Retrieved from: https://www.gov.mb.ca/mit/wms/wmec/index.html

FEMA. (2015). Federal Guidelines for Dam Safety Risk Management, FEMA P-1025. FEMA: Hyattsville, MD. 39 pp.

ICOLD (International Commission on Large Dams). (2016). Bulletin on: Global Climate Change, Dams, Reservoirs and Related Water Resources. ICOLD Technical Committee “Y”. 89 pp.

Interagency Committee on Dam Safety - FEMA. (1979-2004). Federal Guidelines for Dam Safety.. Retrieved from: https://www.fema.gov/emergency-managers/risk-management/dam-safety/federal-guidelines

International Joint Commission (IJC). (2017). A Climate Change Guidance Framework for IJC Boards: Background and Process: A guide for IJC control, watershed, and pilot watershed boards to address climate change within their mandates. International Joint Commission: Washington DC. 33 pp.

Ontario. (2020). Construction (under the Lakes and Rivers Improvement Act). O. Reg. 454/96.

Quebec. (2021). Dam Safety Act. CQLR S-3.1.01.

5 Review of Climate Data for Design and Management of Dam Infrastructure

5.1 Introduction

A review of the climatic parameters that currently exist in the regulations and guidelines used in dam design and operation is presented in this section. An overview of the projected changes in climatic parameters relative to historical climatic conditions is also included.

5.1.1 Climatic Data in Existing Regulations and Guidelines

It is well known that the impacts of climate change will impose higher risks to existing water resources and can have significant implications for flood control, water supply, aquatic habitat, irrigation, etc. The design and planning of dams—as major water resources infrastructure that contribute to social welfare and the economy—is based on climatic parameters such as precipitation, rainfall, evaporation, antecedent soil moisture assumptions and flood peaks, and the probability of occurrence of these parameters. These parameters and their probability of occurrence are expected to change with the effects of climate change, which can impose higher risks to existing dam infrastructure that was designed based on historical climatic conditions. For example, the structural behaviour of dams and appurtenant structures can be impacted by the changes in the ambient air and water temperatures. Changes in design floods and water level variation in a reservoir under climate change are also examples of how climate change can impact dam infrastructure. In addition to the structural behaviour, dam operation and water quality of dam reservoirs can be affected by climate change. Temperature, precipitation, ice condition, and flood and drought are among climate-related factors that can impact the operation of dams and the water quality of reservoirs. The following sections of this report discuss the details of climate change implications for different aspects of dam design and management.

Adaptive management strategies of dams and reservoirs in relation to climate change, particularly the effects of climate change on water quality, is a relatively new concept in Canadian policy and regulation. However, the consideration of climate change in management strategies is becoming more common. For example, the Water Sustainability Act of British Columbia (British Columbia, 2014) lists “the effects of climate change” as a factor only necessitating consideration at the thirty-year review of dam licensing terms and conditions. Older documents include sections on issues such as erosion, water runoff, sun, wind and the need for vegetation on shorelines without any specific reference to climate change (Small Dam Design and Construction Manual – Agriculture and Agri-Food Canada, 1992). Other documents, such as the legislative dam safety reviews in British Columbia, refer to climate change, but consider it as a process that occurs over decades and centuries and thus not applicable to the period of validity of the dam safety review. Similarly, the Ontario’s Safety Reviews for Dam Owners guidance document (Government of Ontario, 2011b) suggests that “the effects of extreme climatic conditions should be assessed as appropriate”, including events such as winter ice formation, but the document does not specifically mention climate change. Ontario’s Geotechnical Design and Factors of Safety guidance document (Government of Ontario, 2011a) does not reference climate change either, although it does include guidelines in relation to changes in mean ground temperature for dam tailings and reservoir foundations that are built on permafrost zones. The aforementioned document also provides guidance on evaluating the “stability of reservoir slopes during heavy rainfall, rapid drawdown, and other loading conditions”, variables that will become increasingly important for management under climate change. Nevertheless, progress is being made in dam management related to climate change through Ontario’s planning for new waterpower projects (Maintaining Water Management Plans, 2016). The Ontario Environmental Assessment Act (1990, currency date December 2, 2021) now includes regulations and technical guidance for all new electricity generation and transmission projects, which includes the Ontario Waterpower Association Class Environmental Assessment for Waterpower Projects (Ontario Waterpower Association, 2018; approved by the Minister of Environment and Climate Change in 2008). The Class Environmental Assessment for Waterpower Projects document (Ontario Waterpower Association, 2018) includes a table where new projects are rated for "facility resilience to climate change" and "climate change impacts (mitigation of)".

As discussed in Section 4.2 of this report, the bulletin from the International Commission on Large Dams (ICOLD) (ICOLD Technical Committee “Y”, 2016) assessed the role of dams and reservoirs in adapting to the effects of global climate change by determining the threats and potential opportunities posed by global climate change to existing dams and reservoirs, and recommended measures to mitigate against or adapt to the effects of global climate change.

“In general, together with a global warming and general average air temperature increase, it is predicted that higher latitudes will get more precipitation and lower latitudes will get less. Therefore, higher latitudes should prepare for more runoff and lower latitudes less. However, the prediction is, for some locals, to have to deal with more frequent significant extremes, greater flooding and longer, more severe dry periods though evolution in extreme conditions is still characterized with high uncertainty. Indeed, if trends in drought events can be stated with significant confidence (more intense, more frequent), trends in floods must be announced with caution: higher precipitation at short time scales may also be compensated by drier soils (particularly for large watersheds), resulting in an uncertain runoff change. This mechanism will be highly dependent on watershed size and climatic region of concern.” (ICOLD Bulletin, 2017)

5.1.2 Available Regulations and Guidelines

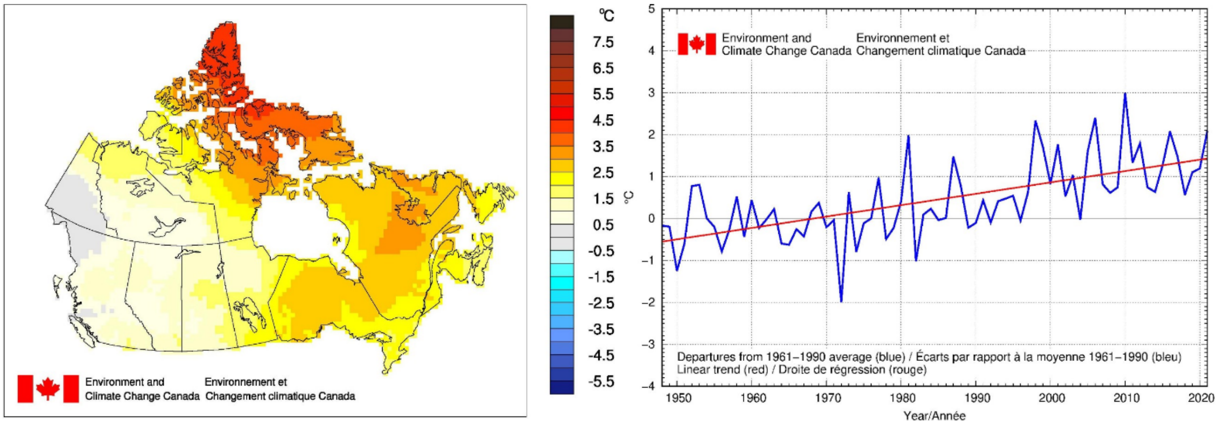
Information about ambient weather parameters such as temperature, rainfall, wind, snow, sunshine and ice is required for the effective design and operation of dams. However, as mentioned in Section 4 of this report, the existing Canadian documentation from the Canadian Dam Association (CDA), the Canadian Geotechnical Society (CGS), federal guidelines and legislation, and provincial and territorial guidelines and legislation either do not include any information about climate change or do not provide any insights into consideration of climate change impacts in design and operation of dams.

5.2 Historical Climate Change and Trends in Canada

5.2.1 Temperature

Although air (and water) temperature may not be a major climatic parameter with obvious impacts on dam operations and safety, it can be an important factor for tailing dams and reservoir foundations that are built in permafrost zones. In addition, changes in air temperature can have remarkable implications for water quality and aquatic life.

According to Environment and Climate Change Canada's (ECCC) Climate Trends and Variations Bulletin (ECCC, 2021), the national average temperature in 2021 was 2.1°C above the average of the 1961–1990 baseline period. Figure 5.1 shows the departure of the 2021 average annual temperature from the baseline period across Canada. Figure 5.1a shows that most of Canada experiences warming and the temperature rise in northern regions is greater than in southern regions. Figure 5.1b shows the departure of the annual average temperature from the baseline between 1948 and 2021 where an increasing trend is apparent.

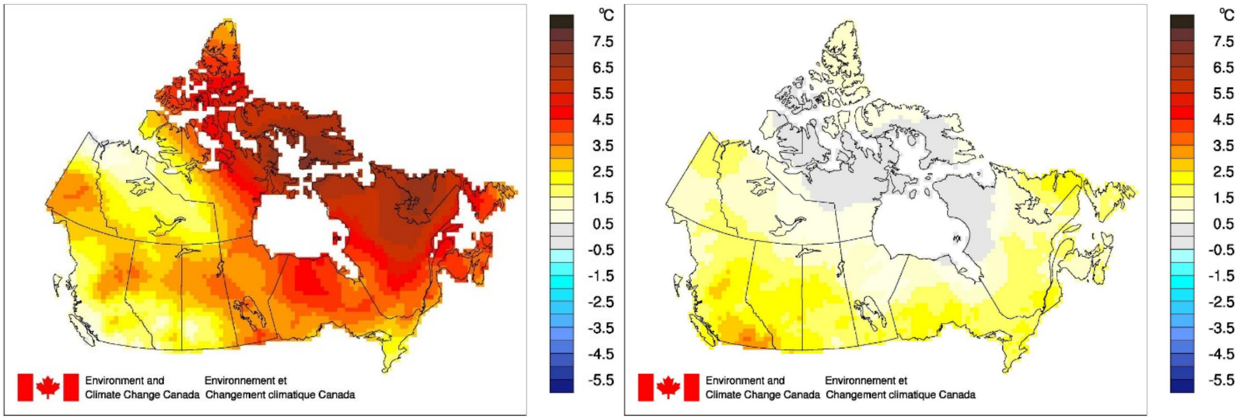


(a) In 2021

(b) Between 1948 and 2021

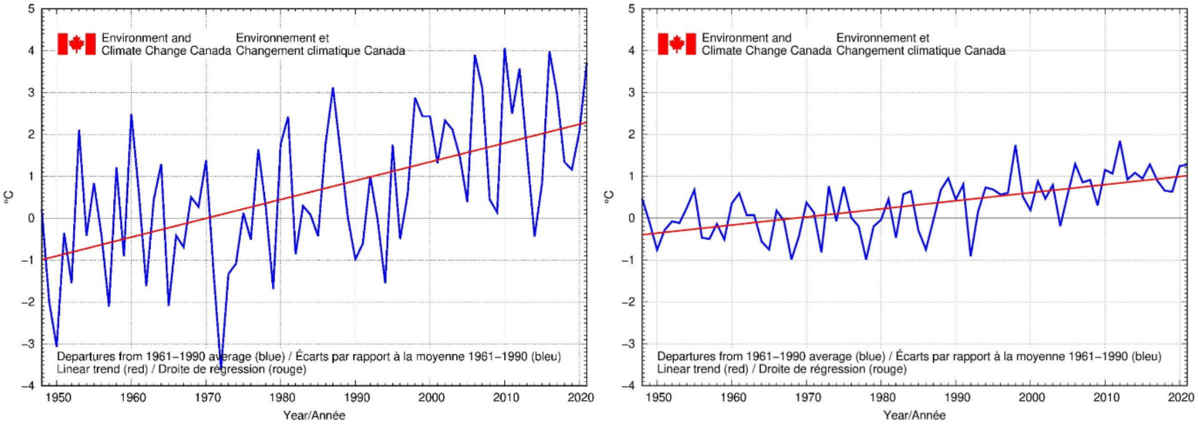
Figure 5.1 Average annual temperature departures from the 1961–1990 baseline period (ECCC, 2021)

The temperature departures from the baseline period are significantly affected by seasonal changes as can be seen in Figure 5.2, where the temperature rises are greater in winter compared with summer. The trend of annual variations in temperature for the winter and summer seasons can be seen in Figure 5.3 and, as expected, the temperature rise is more pronounced in winter.



(a) Winter (b) Summer

Figure 5.2 The 2021 average annual temperature departures from the 1961–1990 baseline period for the winter (December-February of 2020/2021) and summer seasons (ECCC, 2021)



(a) Winter (b) Summer

Figure 5.3 The time series of average annual temperature departures from the 1961–1990 baseline period for the winter and summer seasons (ECCC, 2021)

5.2.2 Precipitation and Rainfall

Historically, the average precipitation in northern Canada is generally much less than it is in southern Canada and, therefore, a percent departure in the north represents much less precipitation than the same percent departure in the south (ECCC, 2016).

In general, it is well documented that changes in precipitation are less spatially coherent. Therefore, the analysis of the national precipitation indices cannot be extended to regional changes in precipitation. As shown in Figure 5.4, the ECCC's Climate Trends and Variations Bulletin (ECCC, 2016) has estimated the national annual precipitation percent departures from the 1961–1990 baseline period and demonstrates that the annual precipitation tends to be heavier than the baseline since the beginning of the 1970s.

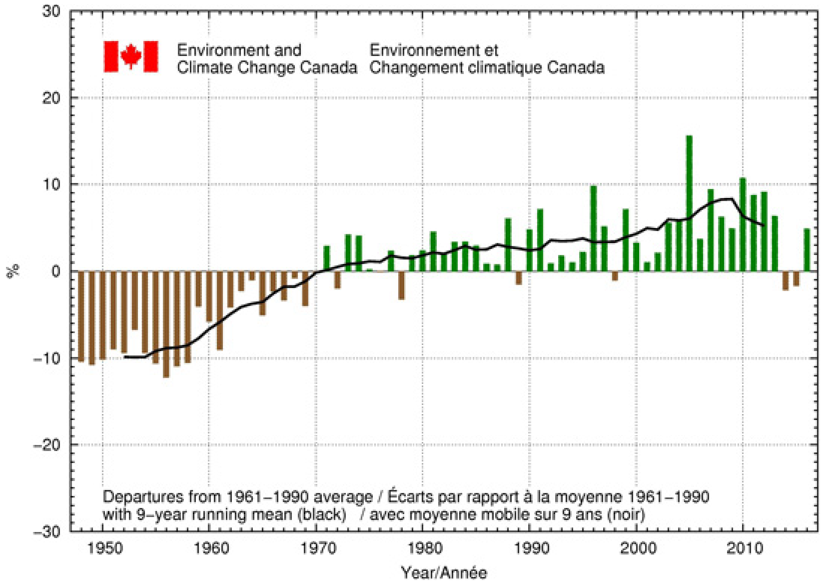


Figure 5.4 National annual precipitation percent departures from the 1961–1990 baseline average (ECCC, 2016)

Vincent et al. (2018) studied the trends in the number of days with precipitation (rainfall and snowfall > 1 mm) across Canada. As shown in Figure 5.5 and as discussed above, changes in precipitation indices are less spatially coherent. For example, an increase in the number of days with rainfall and heavy rainfall is observed at several locations in the south. Similarly, increasing precipitation trends are more pronounced in the southern areas of British Columbia and Ontario. Conversely, a decrease in the number of days with snowfall and heavy snowfall is observed at most stations particularly in the western provinces, while an increase in snowfall is observed in the north. The number of days with heavy rainfall has increased by 2–3 days between 1948 and 2012 at several locations in British Columbia, southern Ontario, southern Quebec and the eastern provinces.

Figure 5.5 Trends in the number of days with precipitation between 1948 and 2012 (Vincent et al., 2018); filled triangles indicate trends significant at the 5% level

Figure 5.6 shows the seasonal trends of the mean precipitation between 1948 and 2012, and although the overall annual precipitation across Canada is increasing (Figure 5.4), precipitation trends vary greatly depending on the season and region. Note that changes in precipitation are computed based on linear trends over the respective seasonal periods; estimates are derived from the gridded station data; and there is a lack of data from northern Canada (Bush and Lemmen, 2019).

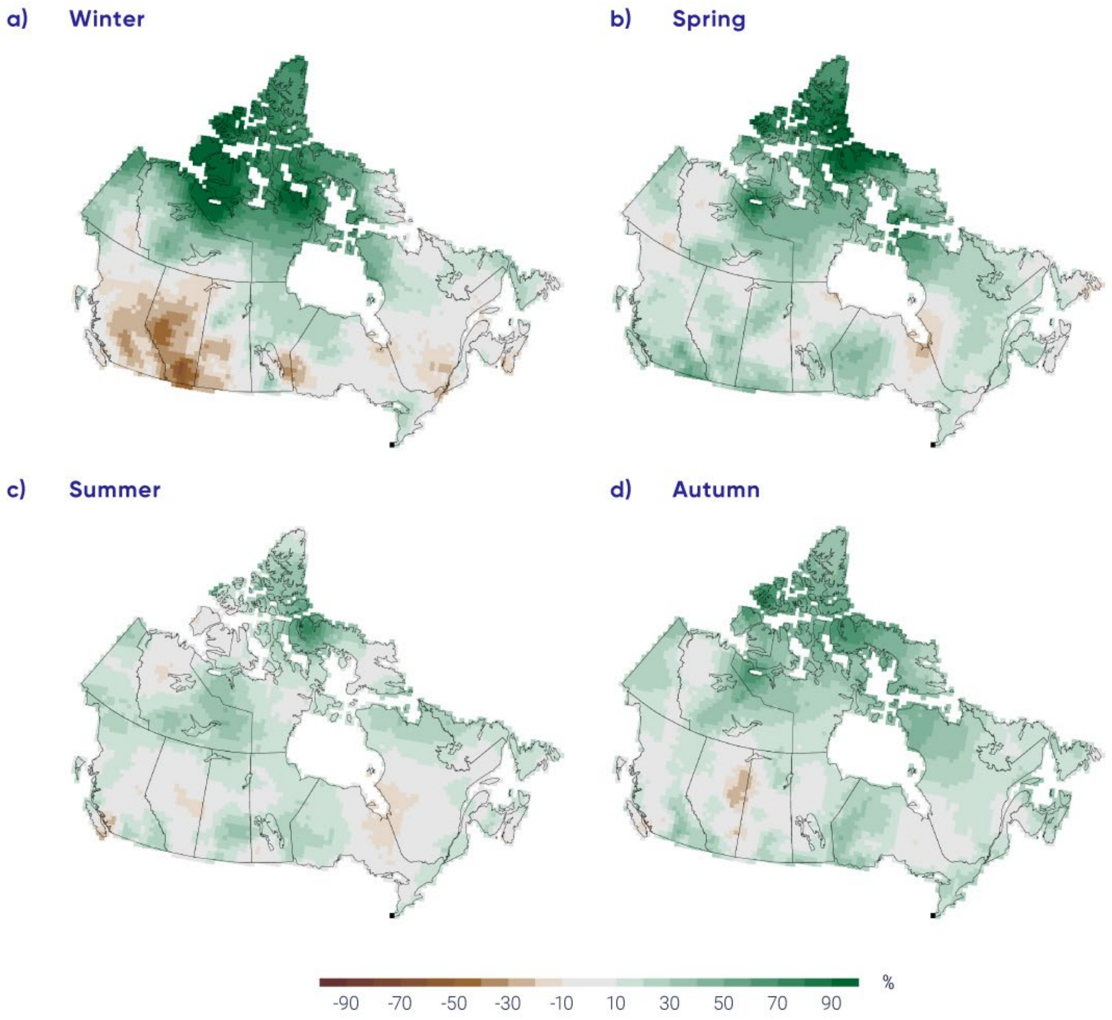


Figure 5.6 Observed changes in normalized seasonal precipitation (%) between 1948 and 2012 for the four seasons (Bush and Lemmen, 2019)

5.2.3 Wind, Snow and Ice

The assessment of mean and extreme wind speeds is challenging due to the limited analyses of available observations and limited research on the mechanisms and causes of observed and projected changes in Canada. Therefore, historical and projected changes in wind speed across Canada were not assessed as part of the Canada's Climate Change Report (Bush and Lemmen, 2019). Other studies have assessed historical trends in mean and extreme surface wind speeds across Canada and showed that surface wind speeds exhibit both decreasing and increasing trends depending on region or season (Cannon et al., 2020).

Through a cascade of interactions and feedback loops, snow can affect the freshwater availability, vegetation, exchanges of carbon dioxide and trace gases, and ecosystem services, which have implications for dam infrastructure. In order to understand changes in snow, multiple variables should be considered, including the snow cover fraction (SCF) and the maximum seasonal snow water equivalent (SWEmax). SCF is characterized as the proportion of days within each month that snow was present on the ground and is affected by the timing of snow onset and snow melt. SWEmax indicates the amount of water stored by snow and available for melt in spring (i.e. how much water is stored in the form of snow), which is of essential importance from a water-resources perspective.

Single point measurements of snow depth from climate monitoring stations may not capture the mean snow depth on the landscape, which is required for detecting trends and variability in snow cover. Moreover, climate stations in Canada are exceptionally sparse above the 55° north latitude and are generally located at lower elevations in mountainous and coastal areas in the sub-Arctic and Arctic. Therefore, the national-scale assessment of snow in the Canada's Changing Climate Report (Bush and Lemmen, 2019) is based on an analysis of multiple datasets—including satellite observations and land surface models—covering the 1981–2015 period.

The SCF decreased by 5% to 10% across most of Canada during most seasons while SWEmax decreased by 5% to 10% across most of Canada during the 1981–2015 period. In contrast, there are parts of British Columbia, Alberta and southern Saskatchewan where increases in SWEmax are evident (Figure 5.7).

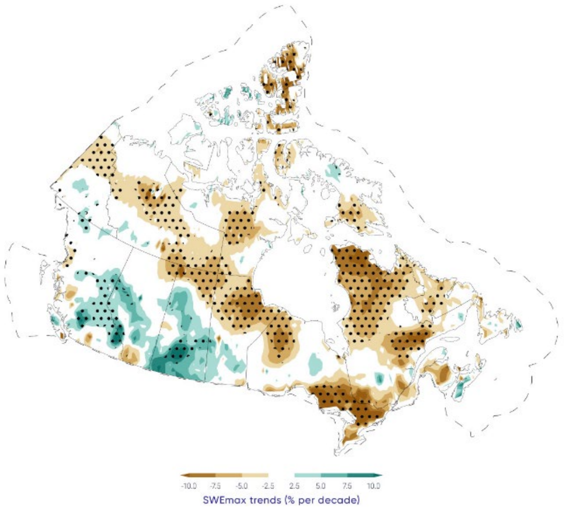


Figure 5.7 Trends in the maximum snow water equivalent (SWEmax; % per decade) for the 1981–2015 period; stippling indicates statistical significance (Bush and Lemmen, 2019)

Surface observations show that ice breakup is occurring earlier and freeze onset is occurring later across small lakes in southern Quebec, Ontario, Manitoba and Saskatchewan. There has been a decrease in the duration of seasonal lake ice cover across Canada over the past five decades due to later ice formation in fall and earlier spring breakup. Moreover, satellite measurements show that lakes in Arctic Canada have also been experiencing an earlier ice minimum (i.e., the last date of floating ice cover on lake surfaces) and an earlier date when the water is clear of ice (Bush and Lemmen, 2019).

5.3 Availability of Projected Climatic Data

5.3.1 Climate Models and Uncertainties

Climate models have evolved within the past decades to become an important tool that provides projections of future climatic conditions. Earth System Models (ESMs) are the latest form of Global Climate Models (GCMs) and can provide a broader picture of future climate on a coarse spatial and temporal resolution. There are various downscaling techniques in the literature that can provide more details for a specific region (point). Greenhouse gases (GHGs) are the main driver of climate change as they alter radiative forcing in the atmosphere. Due to the high uncertainty of future emissions of GHGs, a series of emissions scenarios have been developed by the Intergovernmental Panel on Climate Change (IPCC). Although the most recent (Arias et al., 2021) emission scenarios are based on the Shared Socioeconomic Pathways (SSPs), most climate change impact studies in the literature are based on emissions, the so-called Representative Concentration Pathways (RCPs; Moss et al., 2010). These latter scenarios are used by the IPCC in its fifth assessment report (IPCC, 2013).

Scientific confidence in climate change projections varies by region and by climate variable (Bush and Lemmen, 2019). In general, confidence in the projection of temperature change is higher than that of precipitation. This is mainly due to the fact that temperature change is a direct consequence of the radiative forcing imbalance associated with changing GHG emissions, while precipitation change is governed by a number of complex processes, including changes in the water holding capacity of a warming atmosphere and interactions with topography (Cannon et al., 2020). In addition, lower confidence can be placed in compound events that involve multiple variables (e.g., ice formation).

The projected changes in climatic variables depend on the emission scenario and on how different processes are represented and simulated in climate models. These are the two major sources of potentially reducible uncertainty in climate projections, and they vary based on the assumptions regarding future GHG emissions as well as the climate model and our understanding of the physical processes represented by that model. Internal climate variability, which occurs as a result of the chaotic nature of the climate system, is the third major source of uncertainty and this uncertainty is irreducible.

5.3.2 Climatic Data from Climate Models

Climate modeling has evolved and developed rapidly in the past few decades. There are many climate-modeling groups worldwide developing GCMs and running climate change simulations.

The Coupled Model Intercomparison Project (CMIP) was initiated by the World Climate Research Programme (WRCP) in 1995 with the objective to better understand past, present and future climate changes. An important goal of the CMIP is to make the multi-model output publicly available in a standardized format. Simulation results from different climate groups around the world are provided to the CMIP program. The simulation data produced by models under previous phases of the CMIP have been used in thousands of research papers (some of which are listed here), and the multi-model results provide some perspective on errors and uncertainty in model simulations. This information has proved invaluable in preparing high-profile reports assessing our understanding of climate and climate change (e.g., the IPCC Assessment Reports). The CMIP project has recently moved into its sixth phase (CMIP6), however, most of the existing climate change impact studies in the literature are based on CMIP5.

Although the results of CMIP projects are very useful for assessing future climatic conditions and underlying uncertainties, due to their coarse resolution, they may not be used directly for practical applications. When higher resolution climate data are needed, one can take climate model projections and downscale them to higher resolution over a particular region of interest. Dynamical downscaling involves the use of a Regional Climate Model (RCM) and can provide a higher resolution (e.g., ≤ 50 km) over a limited-area domain. The international CORDEX project is an example of efforts to produce an ensemble of multiple dynamical and statistical downscaling models considering multiple climate models and emission scenarios from the CMIP5.

ECCC developed the Canadian Regional Climate Model (CanRCM4), which dynamically downscales the Canadian Earth System Model (CanESM2) to a grid with a 0.44° (~50 km) resolution over North America (Scinocca et al., 2016). Fifty (50) runs of CanRCM4 under an RCP 8.5 high emission scenario were used to form a Large Ensemble (LE) of projected climatic data (Cannon et al., 2020). The CanRCM4 LE results were used in the Climate-Resilient Buildings and Core Public Infrastructure initiative led by the National Research Council Canada.

The access to sets of several regional climate scenarios has made it possible to undertake more detailed regional and local impact and adaptation studies, and to examine the uncertainty of climate projections in more depth.

5.4 Climate Change Implications for Dam Design and Management

Climate change is expected to affect the climate normals, other climate averages and extreme climatic events, which in turn can affect the design, evaluation, safety, operation and management of dams. Service interruptions and failure of dam infrastructure may result in significant economic losses. The design, operation and management of dams have been based on the historical climatic condition with an implicit assumption of climate stationarity. However, under the conditions of climate change, such assumptions are not valid anymore. Sections 6 to 10 of this report discuss the potential effects of climate change on different aspects of dam design and management for new and existing dams, where various climatic variables may play a role. Therefore, the projected changes in these climatic variables are required to be assessed in order to understand the impacts of climate change on dams. The following sections will provide an overview of the projected changes in climatic data for various climatic regions across the nation.

5.5 Projected Changes in Climatic Data for Dam Design and Management

5.5.1 Temperature

It is clear that Canada's climate has been warming for decades and will continue to warm further in the future. Both the observed and projected increases in mean temperature in Canada are about twice the corresponding increases in the global mean temperature, regardless of future emission scenarios. Between 1948 and 2016, the best estimate of mean annual temperature increase is 1.7°C for Canada as a whole and 2.3°C for northern Canada. Table 5.1 shows the projected changes in temperature for various regions across Canada obtained using multi-model climate change projections for near term (2031–2050) and the late of century (2081–2100) relative to a 1986– 2005 reference period for a low (RCP2.6) and a high (RCP8.5) emission scenario.

Table 5.1 Projected changes in annual mean temperature for different regions and for all Canadian land area, relative to the 1986–2005 period (Bush and Lemmen, 2019)

Region	**Median Temperature (25th, 75th Percentile), ºC**			
	RCP2.6		**RCP8.5**	
	2031–2050	**2081–2100**	**2031–2050**	**2081–2100**
British Columbia	1.3 (0.8, 1.9)	1.6 (1.1, 2.1)	1.9 (1.4, 2.5)	5.2 (4.3, 6.2)
Prairies	1.5 (1.1, 2.1)	1.9 (1.2, 2.2)	2.3 (1.7, 3.0)	6.5 (5.2, 7.0)
Ontario	1.5 (1.1, 2.1)	1.7 (1.0, 2.1)	2.3 (1.7, 2.9)	6.3 (5.3, 6.9)
Quebec	1.5 (1.0, 2.1)	1.7 (1.0, 2.2)	2.3 (1.7, 2.9)	6.3 (5.3, 6.9)
Atlantic	1.3 (0.9, 1.8)	1.5 (0.9, 2.0)	1.9 (1.5, 2.4)	5.2 (4.5, 6.1)
North	1.8 (1.2, 2.5)	2.1 (1.3, 2.5)	2.7 (2.0, 3.5)	7.8 (6.2, 8.4)
Canada	1.5 (1.0, 2.1)	1.8 (1.1, 2.5)	2.3 (1.7, 2.9)	6.3 (5.6, 7.7)

Figure 5.8 shows maps of the projected temperature change for the 2081–2100 summer and winter seasons relative to the 1986–2005 baseline period obtained from the CMIP5 multi-model ensemble under low (RCP2.6) and high (RCP8.5) emission scenarios. The seasonal mean temperature is projected to increase across Canada, with the largest changes occurring in northern Canada in winter (Bush and Lemmen, 2019).

Figure 5.9 shows the projected changes in the January 1% and July 2.5% design temperatures, as well as the minimum and maximum mean daily temperatures as indicators of extreme hot and cold temperatures. Extreme temperature changes are also consistent with warming. Extreme warm temperatures are projected to increase, while extreme cold temperatures are projected to decrease. The magnitude of extreme temperature change is proportional to the magnitude of mean temperature change. Northern Canada is projected to warm more than southern Canada, and winter temperatures are projected to increase more than summer temperatures. Cold extremes experience larger warming in the north, whereas hot extremes warm fastest in southwestern Canada.

It should be noted that, in general, there is a somewhat greater uncertainty for projections of extreme temperature due to higher internal variability and higher uncertainty in climate model performance for extremes.

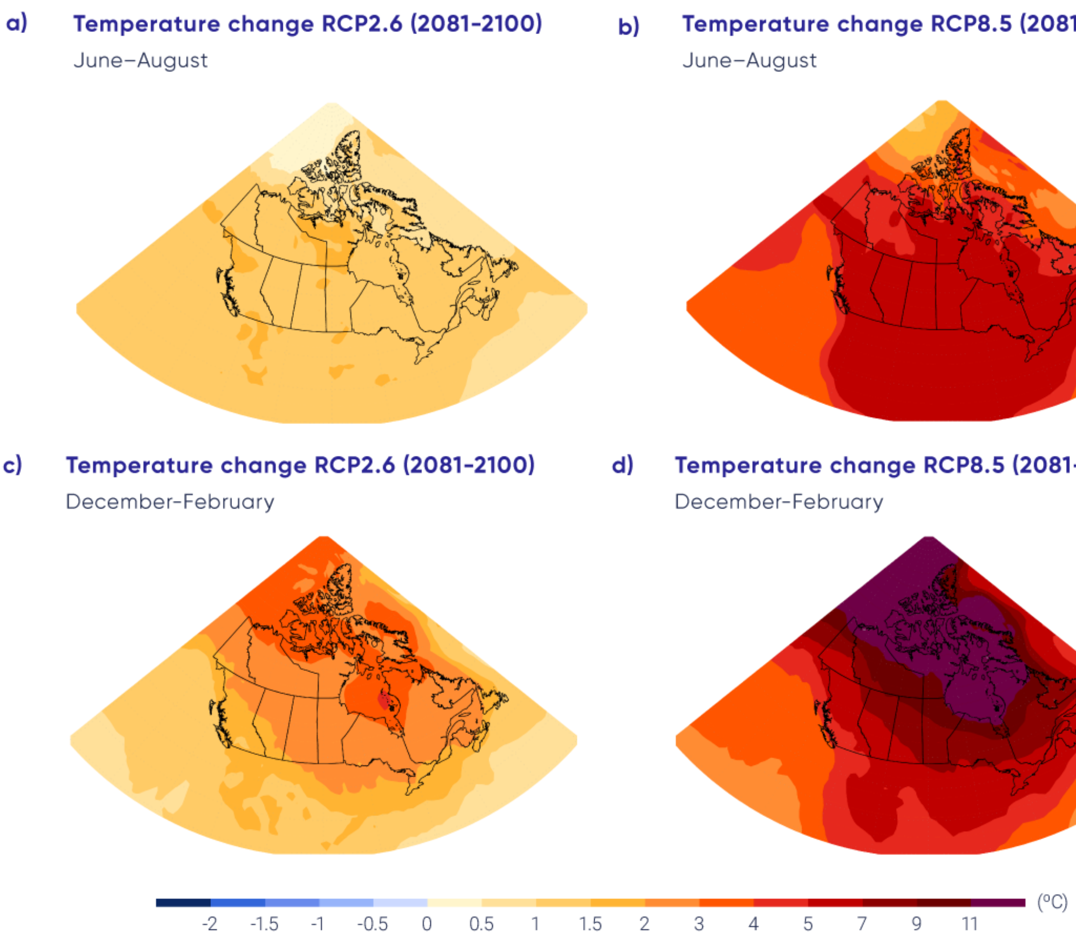
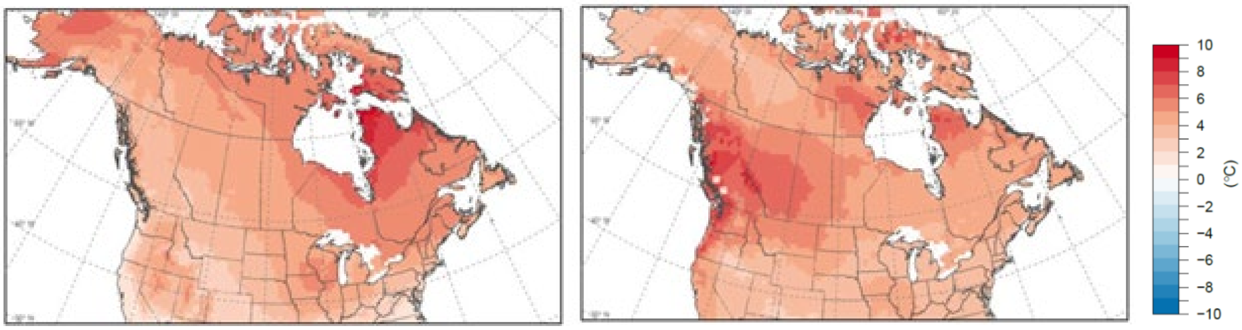
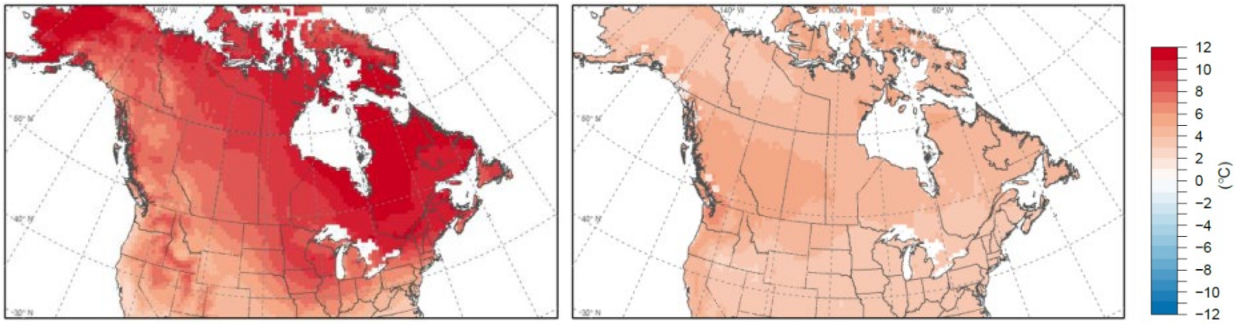


Figure 5.8 Projected changes in temperature for the 2081–2100 (a and b) summer and (c and d) winter seasons relative to the 1986–2005 baseline period under low (RCP2.6) and high (RCP8.5) emission scenarios (Bush and Lemmen, 2019)



(a) January 1% design temperatures (b) July 2.5% dry design temperatures



(c) Minimum mean daily temperatures (d) Maximum mean daily temperatures

Figure 5.9 Projected changes in temperature for 2065–2095 relative to the 1986–2016 baseline period under a high emission scenario (RCP8.5) (Cannon et al., 2020)

5.5.2 Rainfall and Precipitation

Figure 5.10 shows maps of the projected annual and seasonal precipitation change as a percentage for 2081–2100 relative to the 1986–2005 baseline period obtained from the CMIP5 multi-model ensemble under low (RCP2.6) and high (RCP8.5) emission scenarios.

The mean annual precipitation is projected to increase across Canada, with the largest percentage increases occurring in northern Canada. Winter precipitation is also projected to increase across Canada, with the largest changes occurring in northern Canada. It should be noted that since the amount of precipitation in the Arctic is low, even modest changes in the absolute amount of precipitation translate into a large percentage change. Summer precipitation is projected to decrease over southern Canada under a high emission scenario toward the end of the 21st century, but only small changes are projected under a low emission scenario.

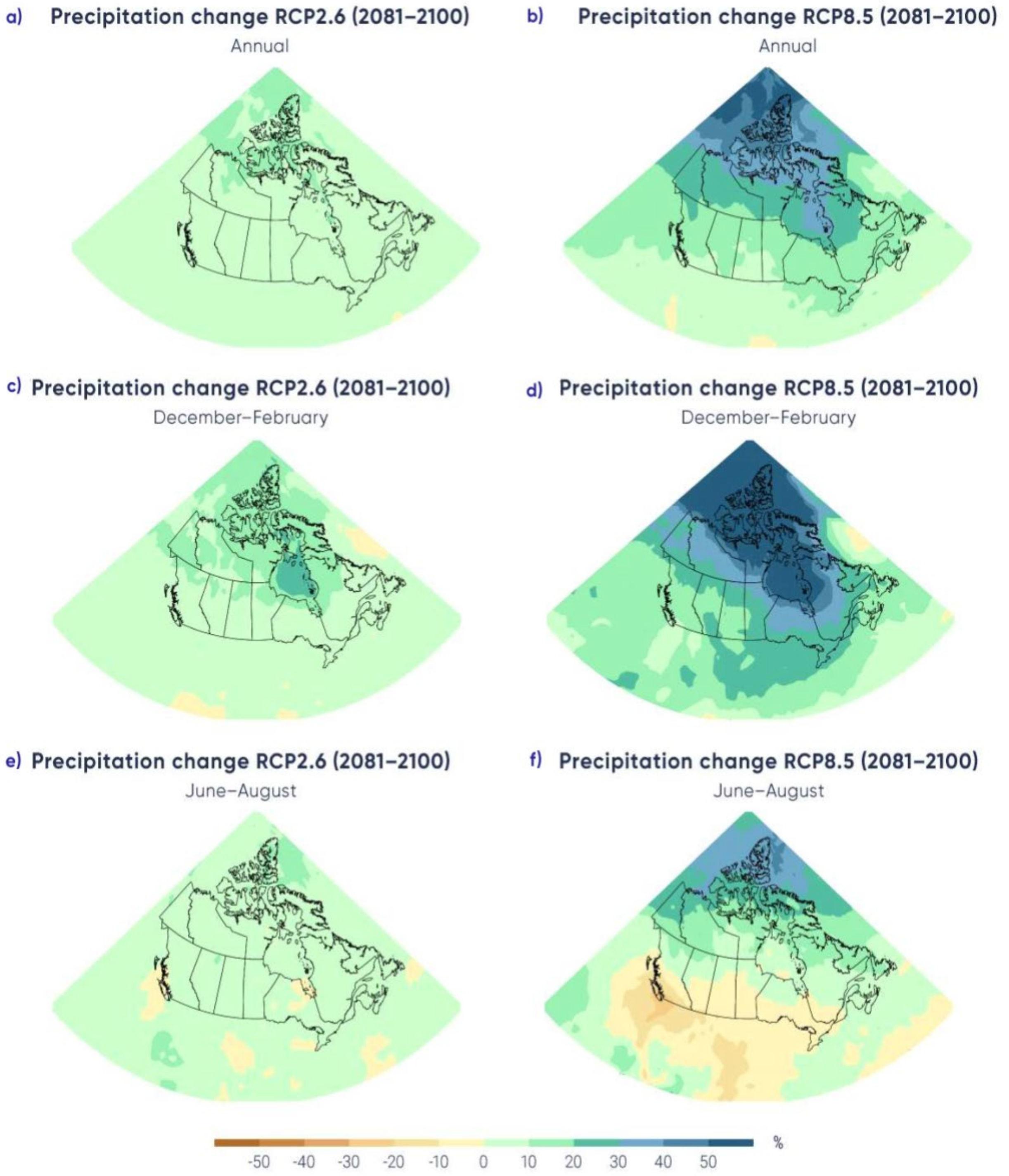
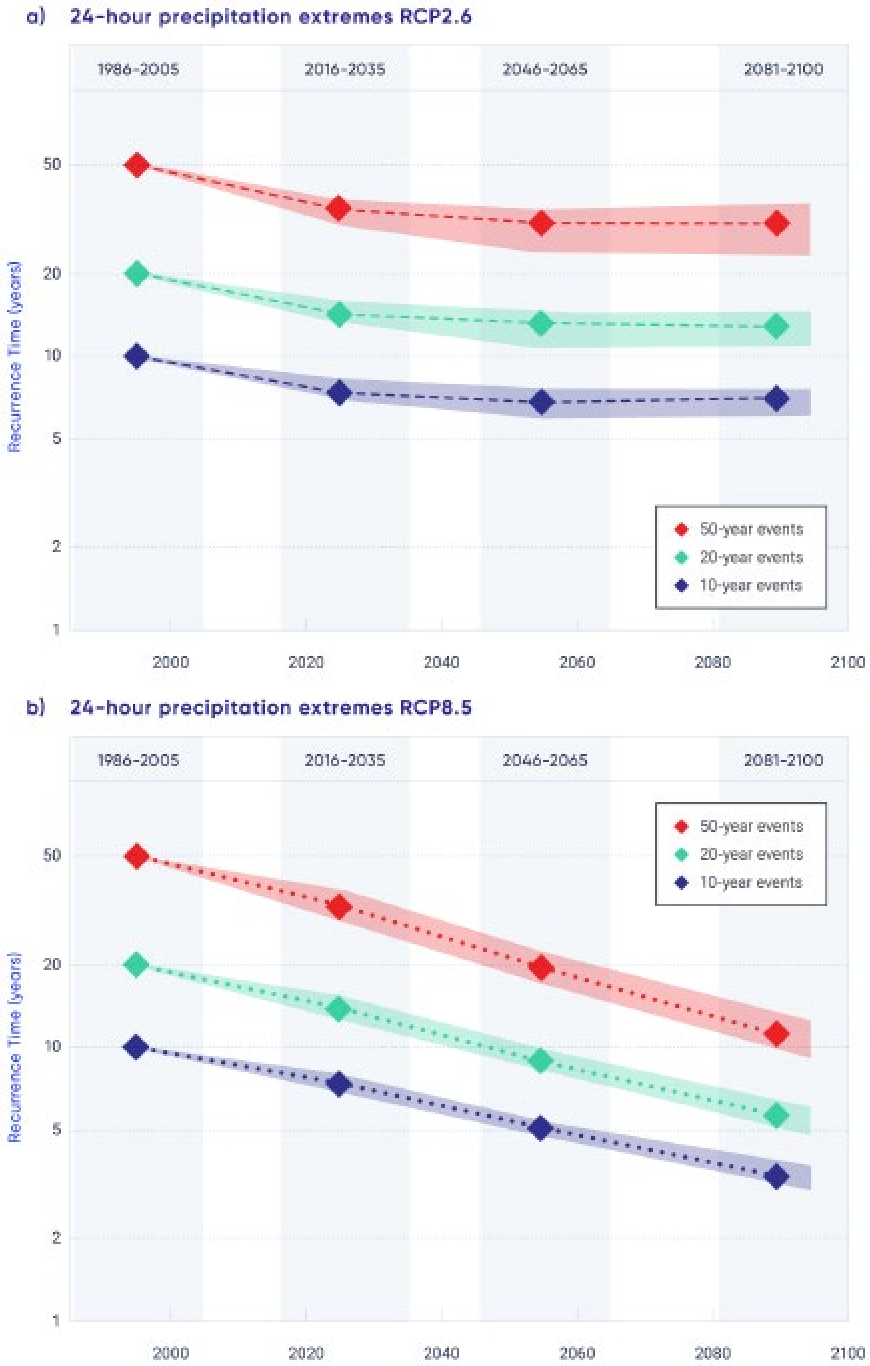


Figure 5.10 Projected changes in precipitation for the 2081–2100 (a and b) annual, (c and d) winter season and (e and f) summer season relative to the 1986–2005 baseline period under low (RCP2.6) and high (RCP8.5) emission scenarios (Bush and Lemmen, 2019)

According to the CMIP5 multi-model ensemble under low and high emission scenarios, extreme precipitation is projected to increase in Canada. Figure 5.11 shows the projected mean changes in the recurrence time for extreme precipitation for once in 10-, 20- and 50-year events. For all of Canada, extreme precipitation with a return period of 20 years in the late century climate is projected to become a once in 10-year event for 2031–2050 under a high emission scenario (Bush and Lemmen, 2019).

The number of 24-hour extreme precipitation events that occur once in 50 years on average is projected to increase by about 10% by 2031–2050 and 25% by 2081–2100 under the high emission scenario, with small differences in the projected percentage changes among various climatic regions of Canada (see Table 5.2; Bush and Lemmen, 2019). It should be noted that due to the coarse resolution of global climate models, the processes at the local scale are not well represented, so projections should be interpreted with caution.



a) 24-hour precipitation extremes RCP2.6

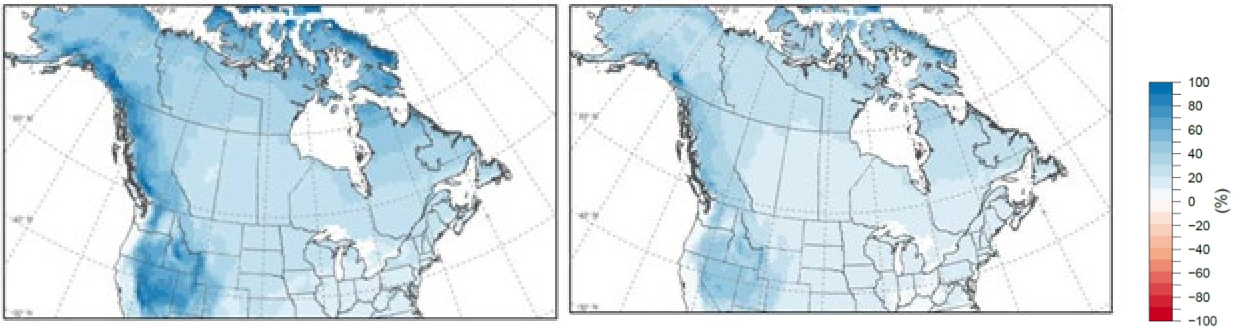
b) 24-hour precipitation extremes RCP8.5

Figure 5.11 Projected changes in recurrence time for extreme precipitation under (a) low (RCP2.6) and (b) high (RCP8.5) emission scenarios; the shaded areas represent the lower and upper bounds of the 25th and 75th percentiles (Bush and Lemmen, 2019)

Table 5.2 Projected changes in the number of annual maximum 24-hour precipitation events that occur once in 50 years on average (Bush and Lemmen, 2019)

Region	**Median (25th, 75th Percentile), %**			
	RCP2.6		**RCP8.5**	
	2031–2050	**2081–2100**	**2031–2050**	**2081–2100**
British Columbia	7.0 (3.0, 10.5)	9.2 (5.1, 16.0)	10.1 (7.5, 15.5)	28.7 (21.9, 33.5)
Prairies	6.1 (2.3, 10.5)	6.5 (2.0, 11.3)	10.0 (6.2, 12.1)	21.3 (14.8, 26.8)
Ontario	4.9 (0.9, 8.4)	7.6 (0.8, 11.0)	8.5 (2.8, 13.0)	20.1 (13.3, 28.0)
Quebec	6.3 (0.9, 9.9)	7.7 (3.3, 11.9)	10.8 (4.7, 17.1)	26.5 (17.9, 33.8)
Atlantic	7.7 (3.5, 12.8)	9.2 (6.6, 14.3)	14.3 (7.9, 21.2)	32.4 (24.9, 42.6)
North	4.9 (2.4, 9.0)	6.4 (1.7, 10.2)	10.8 (7.8, 13.0)	30.1 (24.9, 33.8)
Canada	6.2 (3.8, 9.2)	7.4 (5.0, 10.4)	9.2 (7.0, 11.9)	24.7 (19.6, 29.7)

As the climate warms, particularly in northern Canada, there will inevitably be an increased likelihood of precipitation falling as rain rather than snow, which is consistent with the observed changes in the snowfall fraction (Bush and Lemmen, 2019). Figure 5.12 shows the changes in the annual total rainfall for various regions of Canada where there is a continued shift from snow to rain over time. High latitudes are projected to experience a larger relative increase in the total annual rainfall by the late 21st century (up to an increase of 53% under RCP 6.0 at the end of the century). There is high confidence that annual precipitation and rainfall will increase across Canada with global warming, however, there is low to medium confidence regarding the precipitation projections for more detailed regional areas.



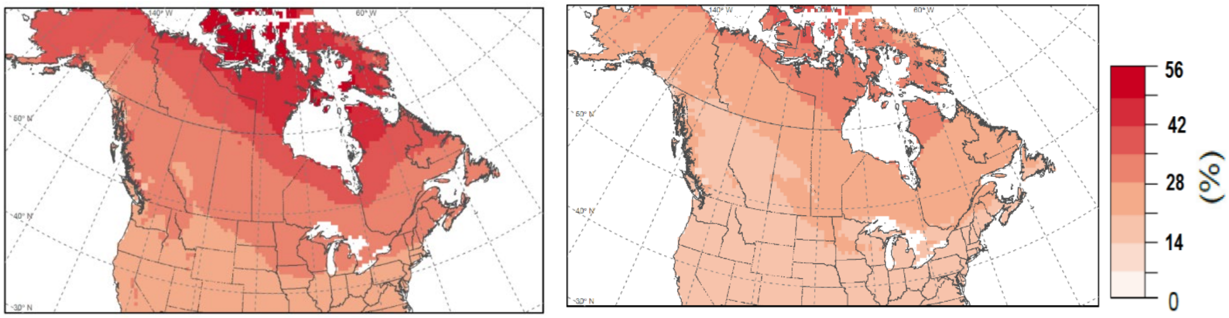
(a) 2065–2095 under RCP8.5 relative to the 1986–2016 baseline period

(b) 2074–2100 under RCP6.0 relative to the 1986–2016 baseline period

Figure 5.12 Projected changes in annual rainfall (adapted from Cannon et al. (2020))

According to Bush and Lemmen (2019), there is lower confidence in the projections of rainfall extremes compared with non-extreme rainfall projections since changes in short-duration precipitation are affected by a number of complex interactions. On the other hand, projections of temperature changes are more reliable than those for extreme precipitation. Hence, temperature scaling—defined as expressing the relative change in precipitation extremes as a function of warming—is an alternative tool to be used as the basis for providing guidance to engineers on future changes in daily and sub-daily rainfall extremes (Cannon et al., 2020; CSA, 2019). The temperature scale used to obtain projected changes in short-duration precipitation follows the theoretical Clausius-Clapeyron relationship that considers a ~7% increase per 1°C. This approach was used in the CRBCPI initiative to estimate the projected changes in extreme rainfall design parameters (Cannon et al., 2020).

Figure 5.13 shows maps of the estimated temperature scaling rates for extreme rainfalls (e.g., 50-year one-day rain) calculated based on mean local annual temperature changes and Clausius-Clapeyron relationships. Since temperature scaling is used for the calculation of extreme rainfall variables, the regional variation of estimated changes in extreme rainfall is similar to those of mean annual temperature. There is high confidence that the annual precipitation and rainfall will increase across Canada. The shift in phase of precipitation from snow to rain with global warming leads to larger relative increases in the rain across Canada. The extreme rainfalls are projected to increase between 20%–46% for nationwide locations under RCP8.5 by the end of the century.



(a) 2065–2095 under RCP8.5 with respect to the 1986–2016 baseline period

(b) 2074–2100 under RCP6.0 with respect to the 1986–2016 baseline period

Figure 5.13 Projected changes in extreme rainfall (adapted from Cannon et al. (2020))

5.5.3 Wind, Snow and Ice

Historical and projected changes in wind speed across Canada were not assessed as part of Bush and Lemmen (2019) and in general, compared to variables such as temperature and precipitation, much less attention has been paid to wind extremes in the existing literature. In addition, the overall uncertainty about historical trends and future changes is also higher. Previous studies have assessed historical trends regarding mean and extreme wind speeds and have reported general decreasing trends across the globe (see Cannon et al. (2020) and references therein). Relatively few studies have assessed projected changes in extreme winds because GCMs cannot resolve small-scale storms that generate extreme wind events. Some studies have evaluated projected changes to mean and extreme wind speeds over North America using multi-model ensembles that showed (1) increases in mean wind speeds for southeastern and northern parts of North America at the end of this century based on the CMIP3 and (2) increases in projected wind extremes for some parts of the southeastern USA and south-central and northwestern Canada, but decreases for most parts of the USA and southwestern and northeastern Canada at the end of this century based on the CMIP5. Cannon et al. (2020) reported relatively small changes in the future extreme winds across Canada, with the strong caveat that little confidence can be placed in the wind projections.

In the Canada's Changing Climate Report (Bush and Lemmen, 2019), projected trends for snow are calculated from the multi-model mean of an ensemble of climate models (Coupled Model Intercomparison Project - CMIP5), using a high emission scenario (RCP8.5). A reduction of 5% to 10% per decade in seasonal snow accumulation (through 2050) is projected across much of southern Canada, which is equivalent to a cumulative loss of 15% to 30% over the entire 2020–2050 period. Across northern regions of Canada, only small changes in snow accumulation are projected because increases in winter precipitation are expected to offset a shorter snow accumulation period. Compared to snow cover, there is greater uncertainty in SWE projections because of greater spread in climate model responses due to the competing effects of temperature and precipitation (Figure 5.14).

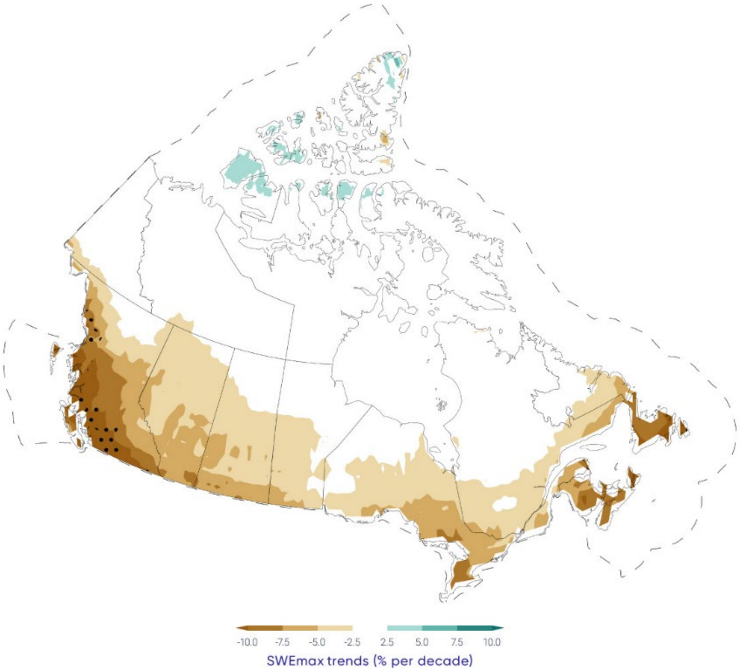


Figure 5.14 Projected trends in the maximum snow water equivalent (SWEmax; % per decade) for the 2020–2050 period under an RCP8.5 emission scenario; stippling indicates statistical significance (Bush and Lemmen, 2019)

The formation of ice and its breakup and disappearance includes several complex processes that involve climate factors such as air temperature, cloud cover and wind. In addition, events such as heavy rains or snowmelt in the watershed can affect the length of time of the freezing. Ice formation and breakup dates are key indicators of climate change and depend on local-scale climatic conditions.

The timing and duration of ice cover on lakes, rivers, reservoirs and other water bodies can affect dam safety and operation as well as the surrounding aquatic habitat. Change in ice cover duration may have different implications; for example, it can change the open-water season, water temperature and evaporation.

Historically, the duration of seasonal lake ice cover has declined across Canada over the past five decades due to later ice formation in fall and earlier spring breakup. In order to obtain projected changes in lake ice, appropriate lake models are required. Under the RCP4.5 emission scenario, lake ice models project that spring breakup will occur 10 to 25 days earlier by the mid-century across Canada (compared with 1961–1990), while freeze-up will occur 5 to 15 days later (Bush and Lemmen, 2019). This results in a reduction of ice cover duration by 15 to 40 days for much of the country. More extreme reductions of up to 60 days are projected for coastal regions. The range in the projected changes is due to regional variability in climatic conditions and to lake-specific variables such as size and depth (Figure 5.15). Mean maximum seasonal ice thickness is projected to decrease by 10 to 50 cm by mid-century, with a more pronounced decrease in the eastern Canadian high Arctic.

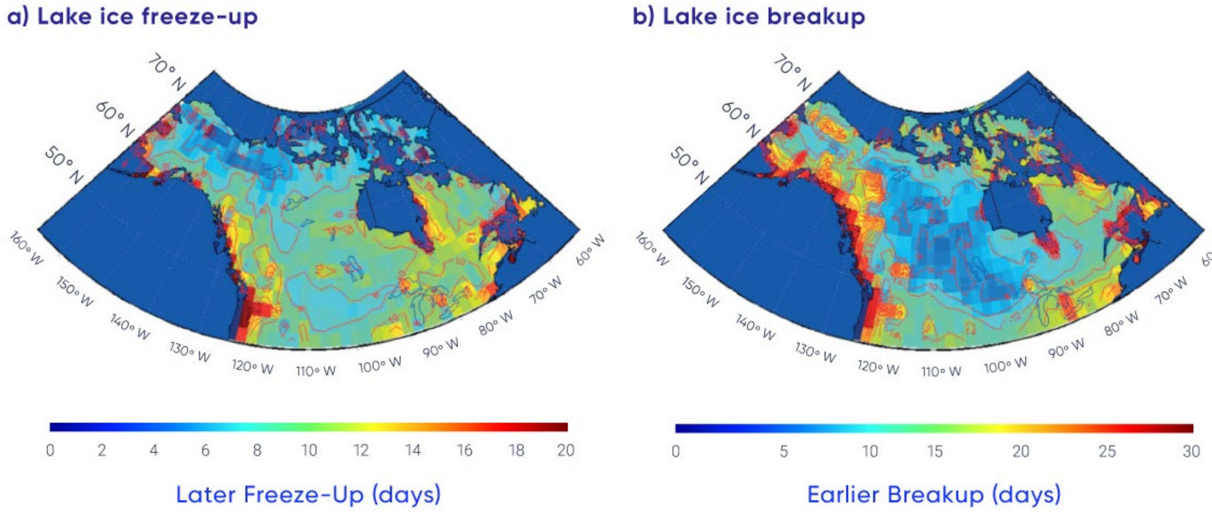


Figure 5.15 Projected change in ice freeze-up and ice breakup dates for Canadian lakes (Bush and Lemmen, 2019)

Future warming is projected to drive an earlier river ice breakup in spring, which is due to the decreased mechanical ice strength and earlier onset 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 (i.e., the increased flow resulting from snow and ice melt in the spring) (Bush and Lemmen, 2019).

5.5.4 Streamflow, Floods and Droughts

The assessment of changes in historical streamflow in rivers and streams is challenging, mainly due to human alterations such as flow regulation, water withdrawals and diversions. Studies on past climate-related changes in streamflow require data, either from streams that are not subject to these forms of human regulation or data from hydrological models that tried to account for those regulations. The seasonal timing of peak streamflow has shifted due to the warming temperatures. Over the last several decades in Canada, spring peak streamflow following snowmelt has occurred earlier, with higher winter and early spring flows. Reduced summer flows have also been observed (Bush and Lemmen, 2019).

In order to assess future streamflow, hydrological models are fed by changes in climate output. However, the multitude of climate and hydrological models used in these studies adds uncertainty to future streamflow changes. Although several regional assessments have been conducted, projected future changes in Canadian streamflow magnitudes have not been extensively examined on a national scale. The findings are mostly consistent with the direction of change, although there are large uncertainties in magnitude.

In general, as stated in Bush and Lemmen (2019) and the references therein:

- Watersheds in British Columbia and northern Alberta are projected to have increases in annual and winter runoff, whereas some watersheds in Alberta, southwest British Columbia, and southern Ontario are projected to have declined in summer flow.
- In the Prairie region, most rivers in southern Alberta and Saskatchewan are projected to have decreased in both annual and summer runoff. However, rivers in southern and northern Manitoba are projected to have increased flow.
- Projected changes in future annual runoff are mixed in Ontario, while in Quebec, the majority of studies project increasing annual flows. A Quebec study using CMIP5 data found that mid-century (2041–2070) flows for southern rivers under RCP4.5 and RCP8.5 will be characterized by earlier and smaller spring peak flow and lower summer runoff.
- Annual mean flow is anticipated to increase in northern regions and decrease in the south. Annual streamflow is projected to increase for New Brunswick and Labrador.
- In northwestern Canada, there is evidence that watersheds such as the Mackenzie and Yukon River basins will see an increase in annual flow, mainly due to the higher precipitation amounts projected at higher latitudes (Bush and Lemmen, 2019).

As for the future streamflow timing, there are few studies in Canada. An earlier snowmelt peak and resulting spring freshet are projected across Canada given the continued projections of spring warming (Bush and Lemmen, 2019).

Streamflow-related floods depend on many climatic factors such as excess precipitation, snowmelt, ice jams, rain-on-snow or a combination of these factors. It is expected that a changing climate will impact several of the factors affecting future streamflow flood occurrence. Generally, projected increases in extreme precipitation are expected to increase the potential for future urban flooding. Projected higher temperatures will result in a shift toward earlier floods associated with spring snowmelt, ice jams and rain-on-snow events. However, it should be noted that projected reductions in snow cover may also impact the frequency and magnitude of future snowmelt-related flooding. Currently, it remains uncertain how the projected higher temperatures and reduced snow cover will combine to affect flooding.

In a warmer world, most climate models project more frequent, longer-lasting warm spells; overall increased summer dryness in the middle-interior regions of North America; and earlier, lessabundant snowmelt. Since Canada is projected to warm in all seasons under a range of emission scenarios, drought risk is expected to increase in many regions of the country. In summer, higher temperatures cause increased evaporation, including more loss of moisture through plant leaves (transpiration). This leads to soils drying more rapidly if the effects of higher temperatures are not offset by other changes (e.g., reduced wind speed or increased humidity). How much summer droughts will increase in frequency and intensity depends on whether future summer precipitation will offset increased evaporation and transpiration. Current climate models suggest that the southern Canadian prairies and the interior of British Columbia will be at a higher risk for drought in the future. However, there is considerable uncertainty in future drought projections. Smaller snowpacks and earlier snow and ice melt associated with warming temperatures could increase drought risk in the many snowmelt-fed basins across Canada that rely on this water source, as well as in regions that depend on glacial meltwater for their main dry-season water supply. Therefore, as temperatures rise, the threat of drought will increase across many regions of Canada.

5.6 Gap Analysis, Future Directions and Workshop Feedback

5.6.1 Identified Gaps

The design, evaluation and management of dams and dam-related structures depend on several averages and extreme climatic loadings that are expected to change under future climatic conditions. For example, the design and planning of dams are based on climatic parameters such as precipitation, rainfall, evaporation, antecedent soil moisture assumptions and flood peaks, and the probability of occurrence of these parameters. These parameters and their probability of occurrence are expected to change under a changing climate, which can impose higher risks to the existing dam infrastructure that are designed based on historical climatic conditions. There is a lack of detailed studies in the literature to provide the projected changes in climatic data for dam design or to quantify the climate change uncertainty and the share of each source of uncertainty. Such information can be also integrated into the decision-making process and help implement projected climatic data in practical applications related to dam management.

5.6.2 Future Directions

In order to respond to the identified gaps above, it is proposed that selected future climatic data for dam design and management are provided through a large ensemble, multi-model, multi-scenario approach. In addition to the projected changes in climatic variables, the share of uncertainty for each source can be quantified. For a number of dam locations across Canada, a tool can be developed to provide such information, together with the downscaled projected climatic data. The proposed project is detailed in Appendix A.1.

5.6.3 Workshop Feedback

The experts in the field have acknowledged that the project addresses a fundamental challenge in dam design and operations. It was suggested that the future phase of the project should focus on specific areas of dam design and operation. Since the climate data and associated uncertainties are expected to continue to improve by the efforts of the international climate change science community, it was also suggested that the next phase of the project will provide guidance for the Canadian dam industry practitioners on how to use the projected climatic data. It was also noted that the project should take into account projected changes in both average and extreme climatic parameters as the needs for the dam design and operations may vary. More details can be found in Appendix B.

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6 Operational Challenges Due to Climate Change

6.1 Introduction

Currently, flow of about half of the planet's major river systems is controlled and regulated by dams (Grill et al., 2019). These dams control one-sixth of the annual continental discharge of water to oceans (Jongman et al., 2012; Hirabayashi et al., 2013). Climate change is expected to increase the risk of flooding globally as well as in Canada, and this is mainly due to the changing spatial distribution, temporal distribution and intensity of precipitation events (Milly et al., 2002; Prein et al., 2017). Dam operations generally alter the frequency, duration and timing of flooding events. Various techniques used to assess global flooding risk have demonstrated that the total global exposure to river and coastal flooding would increase by 3 times from 2010 to 2050 based on population density at risk, and by 2.5 times based on land use (Jongman et al., 2012).

On the other hand, reservoir water surfaces emit a billion tonnes of greenhouse gases each year, mostly through the release of methane from decaying vegetation. This equates to 1.3% of the total annual anthropogenic greenhouse gas emissions globally (Deemer et al., 2019). This makes dams a major contributor to climate change while also being affected by climate change themselves. Therefore, understanding the implications of a changing climate on the operation of dams and vice versa is vital in utilizing appropriate adaptation and/or mitigation strategies.

6.2 Current Operational Challenges and Climate Change

Climate change could affect the various aspects of dam operation and maintenance, which relies significantly on the water balance affected by the changing climate. Water balance has three components: inflow, outflow and demand, and storage and spillover. Various factors affecting water balance components and some of the potential risks and impacted areas are reviewed in detail below.

6.2.1 Inflow

Temperature and precipitation are the two key climatic parameters that are expected to affect dam inflows. Change in temperature has been correlated with changes in precipitation. Environment and Climate Change Canada's (ECCC's) report (Bush and Lemmen, 2019) estimates with medium confidence that annual mean precipitation has increased on average in Canada, with larger percentage increases in northern Canada. Annual and winter precipitation is projected to increase everywhere in Canada over the 21st century, with larger percentage changes in northern Canada. Summer precipitation is projected to decrease over southern Canada under a high emission scenario toward the end of the 21st century, but only small changes are projected under a low emission scenario. For Canada as a whole, observational evidence of changes in extreme precipitation amounts, accumulated over periods of a day or less, is lacking. However, in the future, daily extreme precipitation is projected to increase (high confidence).

The outcomes indicated that in the near term (i.e., 2031–2050), precipitation is expected to increase by less than 10% for all scenarios, while in the long-term (i.e., 2081–2100), the projected changes are higher. It is worth noting that scenarios based on RCP8.5 indicate up to a 10% decrease in precipitation in southern Canada (detailed in Section 5). These long-term changes in precipitation have the potential to change a basin's runoff. These potential changes have been recognized in policy documents such as the report, Impact of Climate Change on Dams & Reservoirs (Atkins, 2013), from the UK.

The inflow variation to dams has also been discussed and estimated in the literature. For example, Zabalza-Martínez et al. (2018) evaluated various future land cover and climate change scenarios and their effect on the Boadella-Darnious reservoir inflow in Spain. That study used the regional hydro-ecologic simulation system (RHESsys) to analyze the impacts from 2021 to 2050 and found a clear decrease (i.e., -31%) in dam inflow for that period. Norouzi (2020) used non-parametric Mann-Kendal trend analysis and showed that inflow to the upstream basin of the Dez dam in Iran would decrease significantly, such that the dam will lose its performance if a water resource management plan was not implemented. In another study, Zareian at al. (2014) used 15 atmosphere-ocean general circulation models to predict the inflow to the Zayandeh-Rud dam from 2015 to 2074 as compared with observed data from 1971 to 2000. The authors showed that the maximum reduction in runoff would occur in fall while the minimum reduction would occur in winter.

As mentioned earlier, the Canadian climate is trending toward warmer winters and increased winter thaws combined with more precipitation as rain. These trends could lead to higher winter high flows causing mid-winter dynamic ice breakups that could increase ice jams and floods with a high level of consequences (Turcotte et al., 2020).

Future climate projections were used to assess the potential impacts of a changing climate on the operation of the U.S. Army Corps of Engineers multipurpose reservoir in east-central Iowa (i.e., Coralville Reservoir) (Landwehr, 2015). That study compared the historical precipitation flow data pre- and post-construction and showed that the inflow volumes increased post construction, resulting in a periodic modification to the water control plan. Additionally, dynamically downscaled climate data and a calibrated hydrologic model of the Iowa River basin was used to evaluate the risk associated with future climate scenarios to the reservoir system. Contrary to the previously mentioned literature, Landwehr (2015) suggested that numerous limitations associated with climate and hydrologic modeling make it difficult to fully assess the risks for a project due to climate change using modeling tools alone. The author also concluded that long-term reservoir planning is not as valuable for meeting the missions of a reservoir as is short-term weather forecasting and a framework that allows for real-time, risk-based decision making for reservoir operations.

Currently, the Canadian Dam Association's Dam Safety Guidelines (CDA, 2013) recommends a 10-year dam safety review interval for dams classified with significant failure consequences (i.e., design flood from 1/100 to 1/1000) and a 5-year interval for dams with extreme failure consequences (i.e., design flood equal to probable maximum flood). It is worth noting that dams with a design flood of less than 1/100 years do not require safety updates. Considering the frequency of these intervals, the long-term impact of climate change on the inflows could be estimated while performing these safety reviews for larger dams. However, since smaller dams with design flood of up to 1/100 years are not required to have regular safety reviews, they could benefit from a guideline on how to account for the changing climate impacts on their inflow forecasts.

6.2.2 Outflow and Demand

Water stored behind dams is often used in various capacities, including municipal use, agricultural consumption, hydropower, etc. Climate change is known to increase these demands. Increases in municipal water demands due to climate change have been documented by many researchers for various regions. In Canada, this could range from 2% (Roshani et al., 2022) to more than 10% of daily per capita consumption per degree of increase in the daily temperature (Akuoko-Asibey et al., 2013; Staats, 2018).

More than 27% of the 482 world’s largest cities (i.e., 233 million people) will have water demands that exceed surface water availabilities by 2050 (Flörkeet et al., 2018). An additional 19% of the world’s largest cities have a high potential for conflict between the urban and agricultural sectors since both sectors cannot obtain their estimated future water requirements. Crop yield has declined by 11% to 21% of the total irrigated acres in the southwestern USA mostly due to surface water shortages (Elias et al., 2016). The North China Plains will witness a 6% increase in agricultural water consumption for wheat under the Intergovernmental Panel on Climate Change’s A2 and B1 scenarios (Mo et al., 2009).

Hydropower plants account for 15% of worldwide electricity production (World Energy Council, 2013). Significant warming (i.e., 6.25°C) is projected to result in a decline of hydropower production in May–June for snow-dominated hydropower plants in India (Ali et al., 2018). The annual mean hydropower would change by -12% to +2%, and spills are projected to change from -49% to +152% in the Peribonca water resource system in Quebec under climate change scenarios by 2050 (Minville et al., 2010). Dams located in colder climates that rely on glacier meltwater might experience an increase in their hydropower production sooner than that. Iceland’s National Power Company has already implemented measures to increase its hydropower production due to increased glacier meltwater (Braun and Fournier, 2016). It is worth noting that the glacier-melting rate is expected to plateau in 2030, remain constant until 2080 and decrease after that. Several Canadian dams in British Columbia, Alberta, Yukon and Manitoba are supplied from watersheds influenced by glaciers' water, therefore, having a better understanding of this subject will be important to the owners and operators of these dams.

These are all good examples of quantified change in reservoir outflows due to climate change. Climate change impacts combined with urbanization, industrialization, population growth, changes in land use, and even an increase in evaporation from reservoirs caused by the rise in temperature would exacerbate the pressure on water demands supplied from dams. These would all increase the need for a real-time decision support tool that predicts the inflows and outflows from dams.

6.2.3 Storage and Spillover

Although the exact mechanism is still uncertain, climate models developed by ECCC indicate that a higher number of extreme events such as urban flooding and droughts are expected to occur in Canada. The models also predict increased coastal flooding in many areas of Canada due to local sea level rise with high certainty (Bush and Lemmen, 2019). There is a good possibility that the change in the distribution, magnitude and frequency of these events will directly influence the hydrological and geological variables used to estimate a dam's reservoir volume, and/or the capacities of spillways or other appurtenances (BC Hydro Generation Resource Management, 2012; Ouranos, 2015; ICOLD, 2016; Turcotte et al., 2019). These changes especially affect hydropower dams.

Blackshear et al. (2011) studied the impact of climate change on various types of hydropower production, where they compared dam types, reservoir sizes and the area to volume ratio of the reservoirs under four climate trends, while accounting for evaporation, discharge, temporal variability and glacier melt. The results indicated that pumped-storage hydro dams were only vulnerable to evaporation and although dams with larger reservoirs were more resilient to the temporal variability of precipitation (i.e., floods, droughts, etc.), these dams were mostly affected by changes in evaporation, discharge and glacier melt. Contrary to storage dams, run-of-river dams were mostly vulnerable to temporal variability, which is expected since these dams often have very negligible storage capacity. It is also worth noting that dams with a high area-to-volume ratio are more vulnerable to evaporation compared with dams with a lower area-to-volume ratio.

Changing climate has been shown to affect the sediment production and transfer processes on hillslopes and through channels, possibly due to changes in precipitation, runoff temperature and land cover. The projected changes in precipitation and air temperature lead to a decrease in sediment yield (-48%) and debris-flow occurrence (-23%) in the Swiss Alps (Hirschberg et al., 2020). In that study, the authors combined a hillslope-channel sediment cascade model with a weather generator based on the climate change projections, which allowed them to quantify the climate change impacts and their uncertainties on sediment yield.

Although the mechanism of how climate change would affect the stability of slopes is still debated, it has been discussed in detail by Chiarle et al. (2011). The authors claim that the stability of slopes is affected by the presence of the cryosphere and its degradation in mountainous regions (e.g., Cordillera of western Canada and the European Alps). The authors also indicated that in lower elevations in the mountains, change in seasonal frost activity, snowmelt and rain on snow events could change the frequency of debris flows.

The gate equipment operation could be affected by cold and ice, as mentioned in the Dam Safety Guidelines (CDA, 2013). As a matter of fact, icing was one of the contributing factors leading to the Spencer dam break in Nebraska, USA, in 2019, preventing the operators from removing the stop logs from the gates (Association of State Dams Safety Officials, 2020). It is very difficult to quantify the impact of climate change on the production of frazil ice. However, delayed formation of frazil ice or absence of ice cover on rivers could potentially cause ice jams and clog intakes and turbines, jeopardizing these assets and their performance (Andrishak and Hicks, 2005; Haley, 2010; BC Hydro Generation Resource Management, 2012; ICOLD, 2016; Turcotte et al., 2019).

ICOLD Bulletin 170 on Flood Evaluation and Dam Safety recommends considering a 25% gated spillway blockage scenario for dams located in forested areas while evaluating the spillway evacuation capacity (ICOLD, 2018). It is worth noting that no specific measure was found in the literature on how to quantify the impact of climate change on ice formation in the context of dams.

6.2.4 Other Parameters Affecting Dams Operation

In the previous sections, most parameters that affect a dams' water balance were discussed. However, other dam-related factors could be impacted by climate change and could indirectly influence dam operation. These include, but are not limited to, the following (please note that these parameters are either discussed in other sections or the literature covering them was too scant to warrant their own section):

- Water quality: Temperature and precipitation have been shown to impact water quality in lakes and reservoirs as discussed in detail in Section 5. Various operation strategies (e.g., releasing times and volume) could affect the water quality as well.
- Environmental water rights: Most large dams are required to release their main river's base flow to satisfy down stream water rights and environmental requirements. Environmental demands could be affected by temperature and precipitation, therefore, these requirements could impact the dam's outflow.
- Pore water pressure in earthen dams: Extreme climatic events (e.g., flooding) are expected to increase due to climate change. Many reservoir dams are designed to capture these floods and store the water for summer and fall use when the precipitation volume is lower. If a dam is expected to overflow during a flood, dam owners often choose to release part of their existing stored water to create room to capture the new flood runoff. This is often performed in a short period and could lead to a rapid drawdown of the reservoir water level. Pore pressure in earthen dams could increase significantly with rapid drawdown events, which has the potential to jeopardize the dam's stability. Climate change could increase the probability of these events and a reliable forecasting system could reduce this probability by providing enough time to perform the water drawdown over a longer period of time.

6.3 Gap Analysis, Future Directions and Workshop Feedback

Current literature on dam operation under climate change has pointed out several areas with clear gaps in the state of the art. A brief list of these areas is presented in the following section.

6.3.1 Identified Gaps

Gaps identified in the literature are briefly outlined below:

(1) Tools to forecast inflows and outflows: Dam operation planning relies heavily on the prediction of inflows and outflows, both of which are influenced by the changing climate. Artificial intelligence has an excellent record of accomplishment in forecasting trends and could be used in this area as well. Having access to a tool that could provide the operators with a robust forecast while accounting for the change in climate could provide them with a vital tool to consider long-term trends in short-term (i.e., daily) operation and decision making.

(2) Operation optimizers: Changes in a dam's inflows and outflows will impact the maintenance schedule, water allocation, sediment washing schedule and turbine operation of the dam. Quantifying these impacts based on expected unit variation in precipitation and temperature will help minimize the risk associated with climate change. The main objective here is to produce various climatic scenarios (both for precipitation and temperature) through model simulation and combine them with a state-of-the-art, multi-objective optimization model while accounting for various dam operation and water allocation requirements. This tool, combined with inflow and outflow forecasting tools, could quantify the impact of climate change on various dam operational requirements while accounting for the uncertainties associated with the changing climate.

(3) Guideline for managing ice and breakup events: Most of Canada is considered a cold climate, where reservoirs and lakes are expected to freeze annually, yet no guideline is available on how to manage these events in dams in general. A warmer climate will increase the frequency of these events. Therefore, quantifying the impact of icing and breakups on various dam operations and providing a general guideline could help dam owners and operators with a baseline on how to manage dams during these events.

6.3.2 Future Directions

Considering the above-mentioned gaps in the state of the art, the following project has been proposed to develop tools to help with forecasting the inflow and outflow of dams and optimize their operation.

Quantifying the impact of a changing climate on dam operation: In order to address the gaps (1) and (2) identified above, this project produces a computer model that helps dam owners and operators predict their inflow and demands. The model then uses these predictions to provide the optimized operation and water allocations based on operational constraints and needs. Finally, various climatic scenarios will be applied to the model and variation of the operation will be quantified under these scenarios. The outcome of this project will allow the impact of climate change on various dam operational requirements to be quantified, while accounting for the uncertainties associated with the changing climate. Further details of this project are outlined in Appendix A.2.

For gap (3) identified above, it is worth noting that the Construction Research Centre of the National Research Council Canada does not currently have facilities to study ice and breakup events and their impact on dam operation (i.e., gap (3)). However, collaborations with other research centers (i.e., Ocean, Coastal and River Engineering Research Centre and Aerospace) could be arranged to define an appropriate project covering this area.

6.3.3 Workshop Feedback

Many good suggestions and consideration were discussed in operation breakout and it was mentioned that some inflow prediction models are currently in use by the industry. Furthermore, it was suggested that short-term outflow prediction might be case specific and may not be as useful in the context of a changing climate. Suggestions were also made to focus more on short-term (i.e., daily) and mid-term (i.e., El Niño) events and their impact in operation rather than focusing on the design event. Additionally, it was recommended to account for different types of debris and their potential to cause blockage. The proponent of the projects mentioned that the proposed models will be designed with simplicity in mind, to be used at the operational level and in a generic manner. This will allow the end user to account for various requirements and constraints while still being able to make decisions. This is an initial and necessary step toward quantifying the impacts of climate change. The long-term downscaled climate scenarios will be applied later on to the decision models to evaluate the changing climate on the operational decision making relative to the status quo. More details can be found in Appendix B.

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7 Water Quality of Reservoirs under Climate Change

7.1 Introduction

Climate change has the potential to impact the water quality of reservoirs across Canada. Given the large number of dams and reservoirs across the nation, the assessment of climate change impacts on water quality in reservoirs and downstream reaches are of essential importance. Thus, future management of dams will necessitate consideration of climate change in operations and policy. The purpose of this section is to scan the literature to answer three main questions regarding the potential impacts of climate change on reservoirs:

(1) What changes in water quality are expected due to climate change?
(2) What characteristics of dam reservoirs will make them more likely to experience these changes to water quality (i.e., which reservoirs are ‘high risk’)?
(3) What are the existing policies and recommended mitigation techniques to help buffer the susceptibility of water quality in reservoirs to climate change?

This review addresses these questions in two main parts:

- Sections 7.2–7.6 explore the specific climate-induced changes that are likely to occur and the effects they might have on reservoirs. Characteristics of reservoirs were examined to determine which features, such as the size and shape of the reservoir or the land use of the catchment area, influence the magnitude of climate change susceptibility.
- Section 7.7 examines the current policies that address adaptive management of dams in relation to climate change and also covers the existing mitigation methods that can be used to improve water quality issues that are intensified by climate change. The outcome of this section will allow cross referencing of potential climate change factors with water quality issues in reservoirs within Canada.

7.2 Climate Change Implications for Water Quality Issues in Reservoirs

Climate change is expected to affect the water quality within reservoirs in a number of ways. The results of the interactions between dam characteristics and climate change parameters are complex and can manifest through a number of pathways that will be discussed in the following sections (see Figure 7.1 and Table 7.1). Water quality issues that are expected as a result of climate change include:

- Increased precipitation during the winter months is likely to cause a greater influx of nutrients and turbidity during spring snowmelt.
- Decreased precipitation during summer months can result in a decrease of nutrient inputs for reservoirs with high external loading from tributaries; or can lead to drought conditions

resulting in higher concentrations of nutrients, contaminants and salinity in reservoirs with high internal loading or point source loading, due to reduced water levels (less dilution).

- Increased occurrence of high wind events can cause increased internal nutrient loading and turbidity by causing resuspension of sediments; it can also result in reductions to stability (reduced stratification) and deepening of the epilimnion (surface layer), which can reduce surface temperatures.
- Increasing temperatures can change the surface temperature of reservoirs, creating more intense stratification, potentially extending the stratified period and leading to anoxic conditions in the hypolimnion.

In addition, the interaction between dam characteristics and climate change effects will include factors such as dam size, stratification and catchment area development, which will be discussed in the following sections.

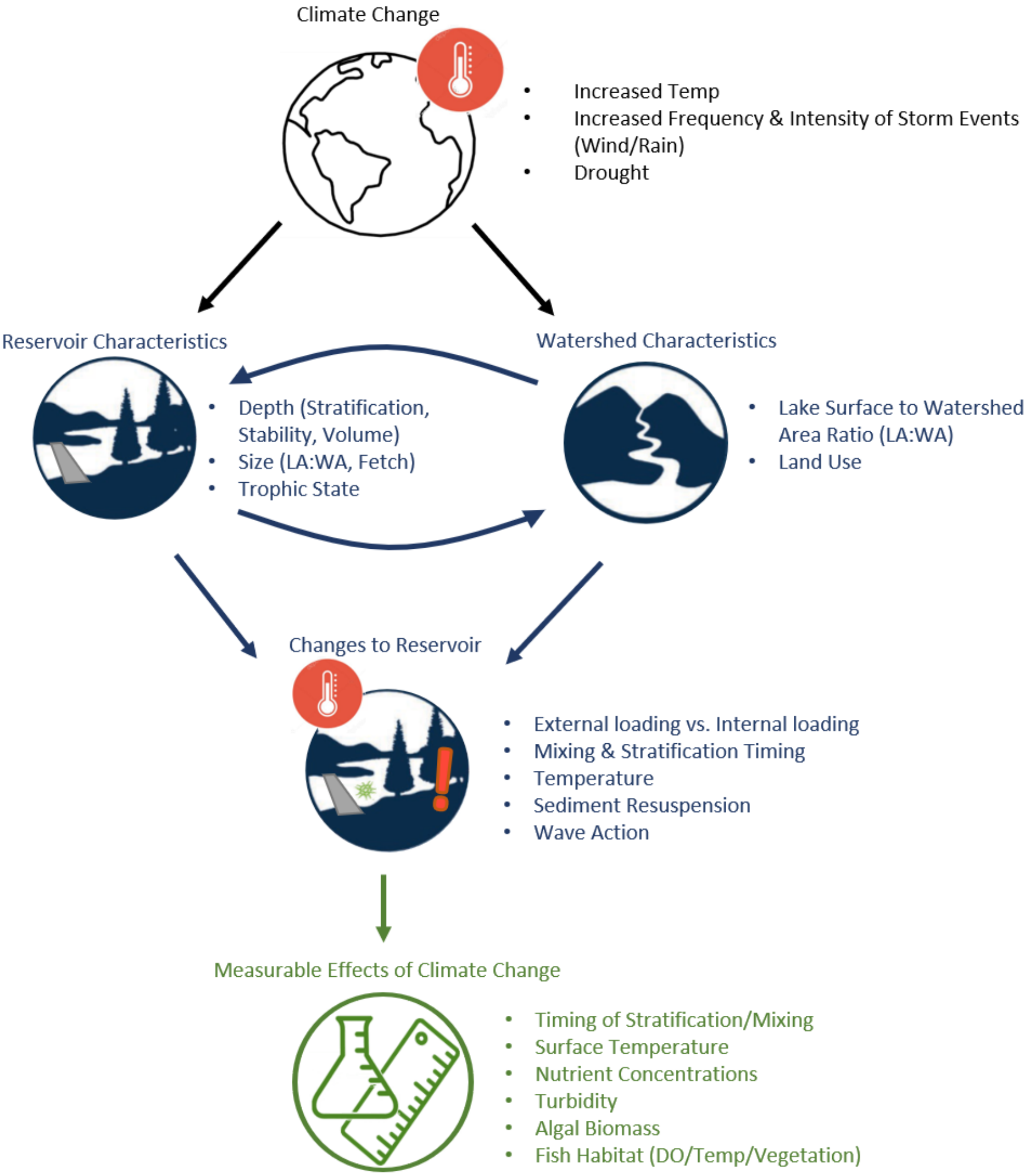

Figure 7.1 Diagram outlining how interactions between climate change, reservoir characteristics and watershed characteristics can affect the water quality of reservoirs (figure adapted from Stockwell et al. (2020) under CC BY 4.0 license)

Table 7.1 Summary of interactions between reservoir characteristics and climate change variables

Reservoir Characteristic	Classification	Climate Change Variable	Interaction	Potential Impact	Potential Vulnerability
Stratification	Stratified	Temperature	↗	Stratification increases the effects of temperature: heating surface waters can create a steeper gradient in the metalimnion and anoxia within the hypolimnion If anoxic conditions develop, internal nutrient loading can increase, which can lead to algal blooms	HIGH
		Wind	↗	Resuspension of nutrients from sediments through mixing Deepening of mixed surface layer can lessen stability and lead to upwelling	HIGH
		Increased Rain	∑	If anoxic conditions develop and internal nutrient loading is high, precipitation could dilute nutrient concentration	LOW
		Drought	∑	If anoxic conditions develop and internal nutrient loading is high, drought could increase nutrient concentration	LOW
	Mixed	Temperature	±	Lack of stratification would mean warming water can be diffused throughout the water column (less noticeable change) Lack of temperature refuges for fish and zooplankton during extreme heat events	MEDIUM
		Wind	↘	Reservoirs that are already highly mixed will be less impacted by wind-driven mixing and resuspension	LOW
		Increased Rain	-	No direct amplification or reduction of effects	
		Drought	-	No direct amplification or reduction of effects	
Size	Large	Temperature	±	Larger volume of water takes longer to heat/cool Larger reservoirs are more likely to be stratified, which could increase effects (see Stratification-Stratified-Temperature above)	MEDIUM
		Wind	±	If surface area is large, increased fetch will amplify the effects of wind If surface area is small relative to volume (high depth), wind effects will be reduced	MEDIUM
		Increased Rain	↘	Larger volume will have less noticeable changes from runoff due to dilution	LOW
		Drought	↘	Larger volume will buffer the impact of changing water levels	LOW
	Small	Temperature	±	Smaller volume will heat/cool faster Small reservoirs are less likely to be stratified, making them less susceptible to the effects of temperature change (see Stratification-Mixed-Temperature above)	MEDIUM

		Wind	±	A small surface area can reduce fetch and, therefore, reduce the amount of wind energy transferred to the reservoir A shallow lake will have greater resuspension of sediment because waves will reach the sediment more easily	MEDIUM

Table 7.1 (continued)

Reservoir Characteristic	Classification	Climate Change Variable	Interaction	Potential Impact	Potential Vulnerability
Size	Small	Increased Rain	↗	External nutrient loading through runoff will have a greater impact on smaller volumes of water	HIGH
		Drought	↗	Decreasing water levels will rapidly affect fish habitat, resuspension and impact of internal loading in smaller reservoirs	LOW
Catchment (WA:LA)	High (Larger Watershed)	Temperature	-	No direct amplification or reduction of effects	
		Wind	-	No direct amplification or reduction of effects	
		Increased Rain	↗	A large watershed relative to lake area will result in greater effects from an increase in precipitation	HIGH
		Drought	↗	A reduction in precipitation could lower nutrient inputs and turbidity entering the lake from the catchment; larger catchment areas are greater sources of runoff	LOW
	Low (Smaller Watershed)	Temperature	-	No direct amplification or reduction of effects	
		Wind	-	No direct amplification or reduction of effects	
		Increased Rain	↘	A smaller watershed relative to lake area will have reduced effects from increased precipitation	LOW
		Drought	↗	A reduction in precipitation would decrease water levels, resulting in an increase to concentrations of nutrients already present in the reservoir	MEDIUM

Symbols used in the table represent various interactions as follows: ↗ indicates that a dam characteristic will amplify a climate effect; ↘ indicates that a dam characteristic will reduce a climate effect; ± indicates that a dam characteristic can either amplify or reduce a climate effect under differing circumstances; and ∑ indicates that a dam characteristic can amplify a climate effect as part of a chain reaction with preceding steps. Note that this table is showing how dam characteristics will amplify or reduce the effects of climate change; for a detailed summary of the effects of climate change, see Table 7.2.

7.2.1 Dam Size

Reservoirs with a large watershed area (catchment) relative to the size of the reservoir itself will be more prone to the effects of changes to precipitation, especially in cases of increased runoff due to snowmelt or storm events.

Reservoirs with higher fetch (surface is relative to predominant wind direction) will experience the greatest effects from the increased wind.

The depth of a reservoir can serve to mediate the effects of increased runoff (i.e., shallower lakes are more likely to respond to high runoff events because of their lower volume). Shallow reservoirs are also more prone to resuspension of sediment by wind. However, interactions with stratification can potentially confound depth-related wind effects in that, if a reservoir is too shallow for stratification to occur, it will have fewer observable changes to water quality (see below).

7.2.2 Stratification

Stratified reservoirs are more likely to show effects from increased wind in the form of changes to thermocline depth, upwell and downwelling, deepening of epilimnion and mixing. The more stable the water column is (steeper temperature gradient across the metalimnion), the more obvious these changes will be.

Depending on the temperature and density of water entering a stratified reservoir from tributaries, water can be subject to plunging flow, interflow or underflow, which can result in uneven distribution of nutrients and turbidity within the water column. This relationship is unique to the conditions of each tributary/reservoir and can change seasonally.

7.2.3 Development of Catchment Area

Both urban and agricultural development within the catchment area were found to be positively associated with water quality changes from all climate parameters. A more developed catchment area results in stronger effects, while more natural forested areas would experience weaker effects.

7.3 Policy, Regulation, and Mitigation

Existing policies for dam regulations in Canada are currently somewhat lacking in guidelines for climate-based management, but examples of regulations used elsewhere in the world provide a good foundation for Canada. This literature review serves as an important first step in identifying the water quality issues that are expected to increase with climate change and the ways to identify dams that are most vulnerable. These results will serve as an important prerequisite for incorporating climate resiliency into future policy decisions.

Climate can be defined as the mean variability of the following three factors over a given period of time: temperature, precipitation and wind (Intergovernmental Panel on Climate Change (IPCC), 2007). Climate systems are controlled by internal dynamics, which are influenced by external factors that include both natural phenomena (e.g., volcanic eruptions) and human-induced changes in atmospheric composition. Relatively rapid human-induced changes to the climate over time have led to changes in the frequency, intensity, spatial extent, duration and timing of weather and climate extremes (IPCC, 2012). Extreme weather and extreme climate events, while intricately related, represent different time scales. An extreme weather event is associated with changing weather patterns within the scale of days to weeks, whereas extreme climate events occur over a longer time scale (e.g., consistent above-average rainfall). An extreme (weather or climate) event is defined by the IPCC as “the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable” (IPCC, 2012). An increase in extreme weather and climate events, such as heavy rainfall, flooding, extreme heat events, drought and wildfires, has been shown to affect water quality in water bodies globally (Figure 7.2; Salila et al., 2020).

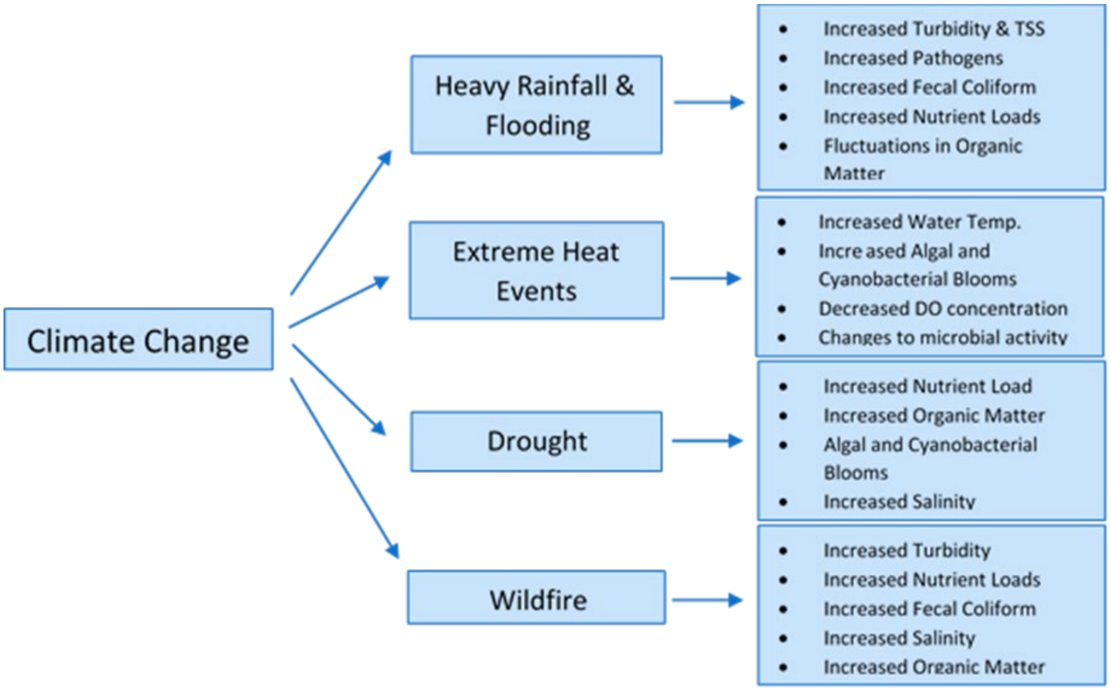

Figure 7.2 Factors related to climate change that affect water quality (figure adapted from Salila et al. (2020) under CC BY 4.0 license)

In Ontario, it is anticipated that both air temperature and precipitation will increase over time, resulting in increases in surface runoff as well as changes in freeze-thaw cycles (Jyrkama and Sykes, 2007; Rahman et al., 2010). Further, variation in predicted streamflow indicates that more extreme events of drought and flood may be experienced (Rahman et al., 2012), bringing forward the question of what changes can be made to dams, reservoirs and catchment areas to mitigate water quality issues exacerbated by climate change. Climate models, including the CGCM3 and NARCCAP, have been used to model the effects of emissions predicted by the IPCC scenarios; these models predict an increase in precipitation, a shift in seasonal variation of discharge (i.e., earlier snowmelt), and increased phosphorus loading for both the Black River tributary in the Lake Simcoe area and Spencer Creek in Southern Ontario (Grillakis et al., 2011; Crossman et al., 2013). A similar study focusing on the Grand River watershed using a PRECIS (Providing

Regional Climates for Impacts) modeling system in conjunction with a hydrological inference model (HIM) predicted an increase in precipitation over the winter months with a decrease in precipitation throughout the summer months, resulting in little change to the total annual precipitation, but a potentially significant shift in seasonal distribution (Li et al., 2016).

7.4 Reservoir and Lake Water Quality under Climate Change

7.4.1 Increased Rainfall and Flooding

The proportion of total rainfall from heavy rainfalls is predicted to increase in the 21st century, particularly in the higher latitudes. Extreme precipitation rates that currently occur every 20 years are likely to increase in frequency, occurring every 5 to 15 years by the end of the 21st century (IPCC, 2012). Increased occurrence of heavy rainfall is likely to affect water quality in a number of ways, including increasing turbidity and nutrient loading. The following sections explore the impacts resulting from these two climate-related events in more detail.

7.4.1.1 Increased Turbidity Due to Rain Events

Runoff from storm events entering a reservoir is often turbid due to suspended sediments, particulates, microbes and other substances. The fate of the particulates carried in the turbid water within the reservoir is determined by the particulate characteristics as well as the temperature and density of the inflowing water. Plunging flow, interflow and underflow are all flow regimes that result from differences in temperature and density between runoff water and the water within a reservoir; all three can have different effects on the thermal stratification and mixing regime of the reservoir (Lee et al., 2015). Modeling efforts have been able to show this relationship, however, results vary greatly depending on the unique characteristics of each reservoir/inflow (Chung and Gu, 1998; Alavian et al., 1992). Inflows of turbid waters from storm events also have the potential to affect light availability in the reservoir water columns. Stockwell et al. (2020) found that changes to light availability (decreasing light availability results in increasing turbidity) were proportional to both the ratio of watershed area to lake surface area (WA:LSA) and to the amount of human development within the catchment. Changes to both light availability and external nutrient loading were mediated by lake volume (Figure 7.3).

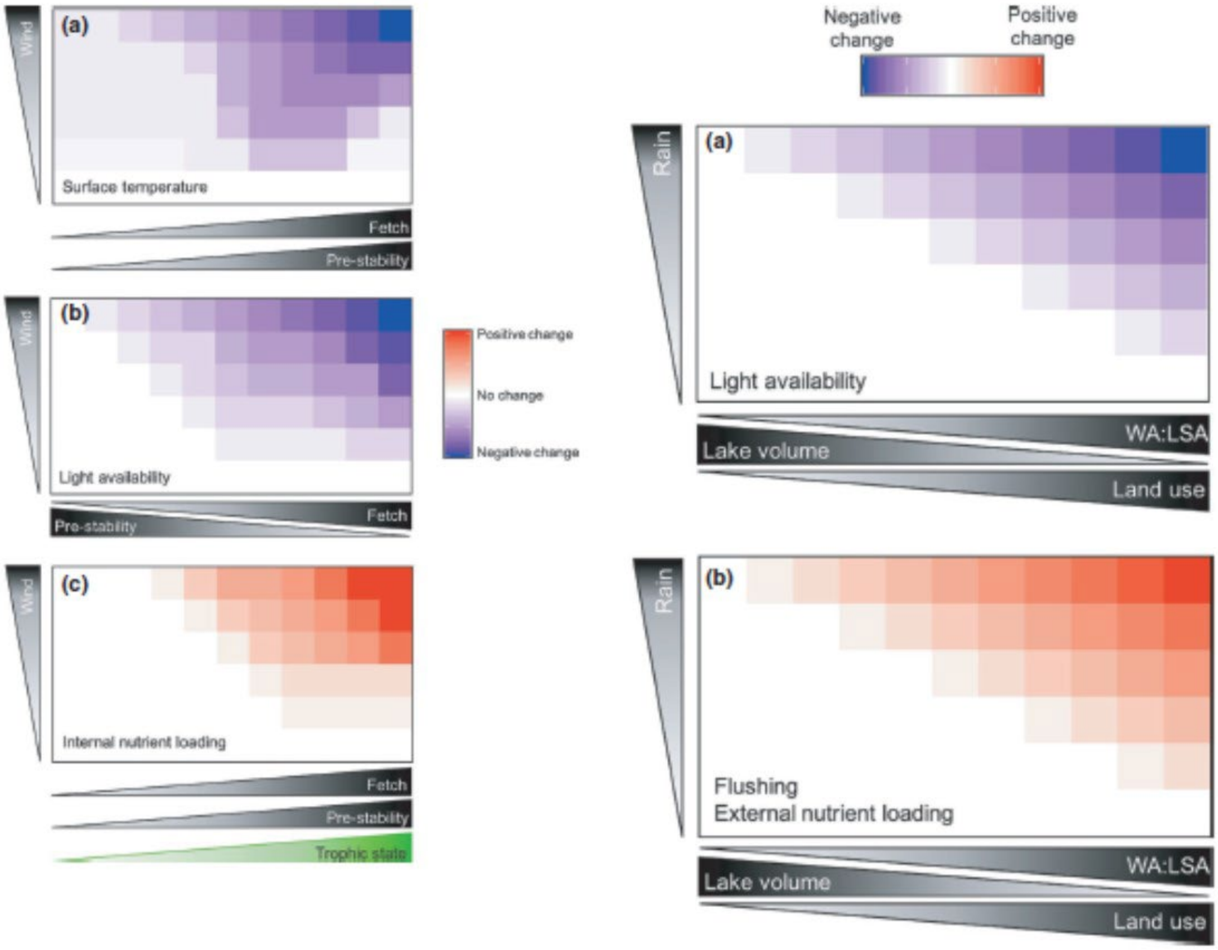

Figure 7.3 Predicted intensity of change and expected direction (positive/negative) resulting from wind or rain events related to the physical parameters of lakes or reservoirs (Stockwell et al., 2020; figure licensed under CC BY 4.0)

7.4.1.2 Increased Nutrient Loading Due to Rain Events

In addition to increases in turbidity and total suspended solids (TSS), heavy rainfall and flooding events have been found to contribute to increases in fecal coliform, nutrients and organic matter levels (Salila et al., 2020). By reviewing literature related to storm events, Stockwell et al. (2020) found that changes to external nutrient loading increased with increasing anthropogenic development of catchment areas and with the WA:LSA ratio (Figure 7.3). Similarly, a study that focused on Lake Auburn, Maine, also found that storm events with heavy rainfall were the main drivers of external phosphorus enrichment and showed that external enrichment due to rain events was exacerbated by land cover changes, such as development (Messina et al., 2020). Chen et al. (2018) measured the change in concentrations of nutrients within a reservoir after a storm event and found an initial decrease in nitrate concentrations as the runoff into the reservoir increased the reservoir volume, which diluted the groundwater inputs, and was accompanied by a rapid increase in phosphate and ammonium. In the following days, water concentrations diminished as the phosphate and ammonium were taken up by algae resulting in an algal bloom, while nitrate returned to pre-storm-event concentrations (Chen et al., 2018).

In a study examining climate effects on dissolved organic carbon (DOC) in Northern Sweden, it was found that the highest concentrations of DOC in snowmelt resulted from the combination of cold winter conditions with little precipitation during the winter and the previous summer, and warmer conditions during the previous fall. The lowest concentrations of DOC resulted from high precipitation in both the summer and winter before the snowmelt, as well as cold autumn conditions (Tiwari et al., 2018).

7.4.2 Increased Frequency of Extreme Wind Events

The occurrence of extreme wind events is predicted to increase with extreme weather events (IPCC, 2012). Although it is clear that climate forecasts project an increase in extreme weather events globally, the effect on aquatic ecosystems is not well understood (Kasprzak et al., 2017). Opportunities to directly observe the effects of extreme weather events on ecosystems are limited because extreme events are rare and stochastic by nature. The following section is a review of the existing literature on how extreme weather events interact with the existing conditions and characteristics of a water body, such as a reservoir, to cause changes in the physical and chemical environments.

Extreme wind events have the potential to resuspend sediments, causing a compressed photic zone. For example, extreme winds led to the decline of submerged vegetation and the dominance of meroplanktonic diatoms following hurricanes that affected Lake Okeechobee, Florida (Beaver et al., 2013). Similarly, an extreme storm in Germany in July 2011 created an opportunity to study the consequences of extreme events and the interaction between the physical and ecological characteristics of a deep, nutrient-poor lake. Wind speeds caused an otherwise clear lake to shift to an exceptionally turbid state. The thermocline deepened, which released cyanobacteria from a deep layer into the surface mixed layer. As a result, intense photosynthesis took place, which increased algal biomass, while the euphotic zone shrank by 8 m for several weeks (Kasprzak et al., 2017). Cyanobacterial blooms are not only promoted by climate warming but can also be triggered by extreme storms.

The impacts of wind events are regulated by both the fetch of the lake and by the antecedent (pre-wind event) stability of the water column (characterized by sharp vertical temperature gradients). Changes to surface temperature and internal nutrient loading are increased with higher fetch and stability, with wind events cooling the surface waters and increasing the amount of internal nutrient loading (Stockwell et al., 2020). On the other hand, change in light availability decreases with higher pre-stability of the lake and increases with higher fetch, meaning that the more stable the lake is prior to the wind event, the less change there will be to light availability (Stockwell et al., 2020). These results are due to the buildup of cold nutrient-rich water below the hypolimnion in lakes with high antecedent stability. The difference between surface and hypolimnetic water facilitates the greatest changes to both surface water temperature and internal nutrient loading or the upwelling of nutrients (Figure 7.3). Depth can also play an important role in determining the effects of a wind event; shallower lakes are more prone to resuspension of particles (Baldwin et al., 2008; Messina et al., 2020), whereas deeper stratified lakes are more prone to nutrient upwelling (Stockwell et al., 2020). The mixed-layer depth usually returns to previous levels within days to weeks after a mixing event, but other ecosystem changes may persist for much longer, such as lowered water clarity or greater oxygen depletion and phytoplankton biomass (Jennings et al., 2012).

7.4.3 Increased Occurrence of Drought

The intensity of droughts is predicted to increase in some seasons and areas as a result of reduced precipitation and increased evapotranspiration (IPCC, 2012). In Ontario, modeling efforts by Li et al. (2016) predicted a significant reduction in precipitation throughout the summer months, potentially causing drought conditions in some regions. Droughts have been found to have varying effects on water bodies depending on their characteristics. Lower amounts of inflow during droughts can lead to a reduction in dilution and flushing that can cause increased salinity, turbidity and higher concentrations of nutrients. However, in some lakes, reduced inflow can lead to a decrease in nutrients and turbidity due to the reduction of catchment inputs and the effects of internal processes such as biological activity and the settling of particulates (Mosley 2015). Increased hydraulic residence times and higher temperatures can lead to intensified thermal stratification (Baldwin et al., 2008; Mosley, 2015). Lower water levels during drought conditions also cause greater potential for wind-related water quality issues, including resuspension of nutrients, mixing and alterations to the stratification of water bodies (Olds et al., 2011; Stockwell et al., 2020). This is due to a decrease in the ratio of depth to lake surface area (Stockwell et al., 2020).

Prolonged drought conditions caused changes in chlorophyll a, turbidity and dissolved oxygen (DO) in the Nebraska Reservoir during droughts in 2002 and 2003. In general, both chlorophyll a and turbidity increased, whereas DO decreased. Along with general trends, a gradient was established with higher turbidity and DO concentrations near the headwaters and the lowest DO concentrations toward the dam itself; this gradient did not exist prior to the drought period (Olds et al., 2011). The gradient of turbidity and chlorophyll a was likely due to the increased residency time and reduced runoff entering the reservoir from the catchment area.

7.4.4 Increasing Temperature

Models predict that the frequency and magnitude of warm daily temperature extremes will increase substantially by the end of the 21st century. The length, frequency and/or intensity of warm spells and heat waves are also predicted to increase (Jyrkama and Sykes, 2007; Rahman et al., 2010). In the Northern Hemisphere, a 1-in-20 year hottest day is likely to start occurring as a 1-in-5 year hottest day (IPCC, 2012). Extreme heat events have been found to be associated with algal and cyanobacterial blooms and decreased concentrations of DO (Messina et al., 2020; Salila et al., 2020). Temperature is a major controlling factor of thermal stratification in water bodies, such as reservoirs. Changes in thermal stratification can have significant effects on water quality by altering nutrient loadings, phytoplankton abundance and water chemistry.

Modiri-Gharehveran et al. (2014) used a water quality model to simulate reservoir response to 21 different climate change scenarios using air temperature and inflow rate as the model inputs. The authors found that increased air temperature significantly affected the onset time of thermal stratification, causing it to occur earlier in the year and for a longer duration. Similarly, several studies also found that an increase in air temperature resulted in an increase in surface water temperatures and an exaggeration of the thermal gradient across the metalimnion (Modiri-Gharehveran et al., 2014). Thermal stratification of reservoirs creates temperature differences at different depths of the dam. Consequently, dams can have a large impact on nearby biological communities by concentrating warm (epilimnion) or cold (hypolimnion) water temperatures before their release downstream (Olden and Naiman, 2010; Li et al., 2021; Murphy et al., 2021). Therefore, dams may be exaggerating the effects of increased climate temperatures through increased thermal stratification and the concentration of water temperature extremes.

7.5 Dam Reservoir Susceptibility to Water Quality Issues

This section identifies characteristics of dams and reservoirs that should be considered when assessing vulnerability to climate change impacts on water quality. These characteristics include dam height, volume and depth of the reservoir, vegetation cover, diversion of water around natural stream beds, local land use, and human population distributions.

By reviewing publications related to water quality within dam reservoirs, the reservoir characteristics that contribute to, amplify or reduce the risk of the aforementioned water quality issues will be listed and described.

7.5.1 Size of Dam and Reservoir, Stratification, and Turnover Time

7.5.1.1 Size of Dam and Reservoir

As dams and reservoirs differ in size, the varying ratios between water surface area, water volume and shoreline length create varying levels of vulnerability to water quality changes. Reservoirs with lower ratios of shoreline length to surface area (or reservoir volume) are likely to have a stronger pelagic and hypolimnetic influence on reservoir water quality than those with higher ratios, making this ratio a good indicator for the vulnerability index assembled by Leigh et al. (2010). Large- and medium-sized reservoirs with large water depths are very likely to see thermal stratification. With increased temperatures due to climate change, the period of stratification is expected to lengthen, resulting in anoxic conditions in the hypolimnion and the release of nitrogen, phosphorus, organic matter and ions (Trumpickas et al., 2009; Liu et al., 2020). Depending on the size of the reservoir, the rate at which the temperature of the water increases will determine the effects that an increase in pH and a reduction in DO will have on this process, as DO is affected by increased nutrients and associated primary production (Atkins, 2013).

In addition to temperature increases, the vulnerability of large reservoirs to water quality changes is expected to be intensified by climate change through more frequent/intense storm events. Lake surface temperatures, light availability and internal nutrient loading are expected to increase with increasing surface area during wind impacts. This is due to larger lakes experiencing higher wind speeds than smaller lakes since larger lakes have a longer fetch and are likely to experience stronger wind-induced mixing (Stockwell et al., 2020). As the frequency of extreme wind events increases, high surface area reservoirs have less time to recover and are more vulnerable to further changes (Stockwell et al., 2020). Further, high precipitation events will likely intensify and increase in Ontario (Jyrkama and Sykes, 2007), leading to more erosion and greater sedimentation (Stockwell et al., 2020). In large reservoirs, Kennedy et al. (1982) identified how sedimentation and uptake of nutrients by algal communities create a gradient of phosphorus and turbidity from the highest concentration in the headwater to the lowest concentration near the dam, while the concentration of chlorophyll was found to increase when moving from headwaters and toward the dam. The increase in the number of extreme wind events is expected to impact water column mixing on most water bodies, while large, high surface area reservoirs will likely be the most susceptible to the resulting water quality issues.

7.5.1.2 Residence Time and Stratification

The size of the reservoir can be linked to the extent to which stratification occurs, while climate conditions can accentuate the layering of the water column. Larger reservoirs with longer water residence times undergo greater thermal stratification, which in turn allows for dissolved nutrients to accumulate in the bottom layers (Marcé et al., 2010; Marion et al., 2017). Stratification periods are expected to lengthen with increasing water temperatures over time due to climate change, leading to increased risks of significant hypolimnetic oxygen deficits in late summer (Trumpickas et al., 2009). When the hypolimnion is in an anoxic state during thermal stratification, an increasing amount of reducing substances and nutrients will be released and settle within this zone, reducing water quality and resulting in eutrophication (Liu et al., 2020).

The vulnerability of reservoirs to water quality issues has been linked to the age of the dam as well as the residence time of the water. Increased water residence time correlates with increased net loading of nutrients, promoting algal blooms and other water quality issues (Leigh et al., 2010). The age of the dam also indicates vulnerability as older reservoirs have increased stores of nutrients, resulting in siltation and reduced water depth, allowing for nutrients from sediments to be more readily available for algal growth in surface waters (Leigh et al., 2010). Burford et al. (2007) conducted a study to compare both the reservoir and watershed characteristics in relation to algal blooms. Their findings describe the likelihood of reservoirs trapping nutrients and highlight how low, calm water, low light attenuation and relatively long resident times can couple with anoxic bottom water conditions due to stratification to increase the likelihood of algal blooms (Burford et al., 2007). Conversely, when dams are first built, the flooded area has a high volume of organic matter that goes through decomposition, a process that requires the consumption of oxygen and results in the release of CO_2, minerals and nutrients (Tremblay et al., 2005). With increasing water temperature, this process can become more intensified, changing the quality of the water further within the first 10 years of a dam’s lifespan through the decomposition of matter from the former terrestrial environment (Tremblay et al., 2005).

7.6 Physical Characteristics of Reservoir and Catchment Area

7.6.1 Reservoir Depth and Flow

If reservoirs exceed a certain depth and flows are slow enough, thermal stratification is more likely (Leroy and Hart, 2002), leading to the potential development of anoxic hypolimnic conditions that can result in nutrient release and reduced water quality (Liu et al., 2020). Further, there is an increased risk of algal blooms in summer resulting from lower water levels and more stagnant water with nutrient-rich inflows associated with storm events (Atkins, 2013). Conversely, larger, more frequent high flows are expected to increase DOC in the water (Atkins, 2003). This would make DOC readily available for decomposers that will subsequently release CO_2, thereby decreasing the pH of the water and contributing to more anoxic conditions, which will further alter other water quality parameters (Tremblay et al., 2005; Liu et al., 2020).

7.6.1.1 Sedimentation

Sediment capture by dams reduces reservoir storage capacity and impairs dam functionality; the rate of sedimentation varies greatly because of spatial variation in sediment supply and delivery that is controlled by basin geology, slope, drainage density, and land use or cover (Leroy and Hart, 2002). Consequently, long-term accumulation of sediment can eliminate the capacity of flow regulation, which is crucial for reservoir functions of water supply, energy production, navigation and flood control (Schleiss et al., 2016). As a dam traps the sediments in an upstream reservoir, river morphology and ecology are altered, resulting in consequences on water quality (Schleiss et al., 2016). It is expected that with climate change, prolonged dry periods will result in very dry and loose soil and there will be greater sedimentation associated with storm events (Atkins, 2013). This increased sediment input can cause problems with turbidity and may create unsuitable conditions for existing species, throwing off the balance of once-healthy ecosystems (Atkins, 2013). Further, high rainfall resulting in increased sedimentation during flooding events can lead to a reduction in water storage capacity as well as water quality and water clarity issues (i.e., increased treatment requirement) (Atkins, 2013). The process of sedimentation is highly linked to the shoreline/landcover in the catchment area, as areas more susceptible to erosion will only ever contribute to the sediment accumulation and the resulting impacts on water quality (Atkins, 2013).

7.6.1.2 Characteristics of Catchment Area

Land use in the catchment areas of reservoirs is an important factor for water quality, and is a focal subject in the literature on reservoirs. Vegetation type influences catchment hydrology, primary production and organic matter inputs, and has effects on soil composition, soil chemistry and, in turn, drainage water quality (Gough et al., 2016). Thus, land alteration in a catchment area can create differing impacts depending on the extent of change and anthropogenic activities within these areas. Agricultural land use has been widely studied since land change and the use of fertilizers has been linked to many changes in freshwater water quality. Agricultural land use can lead to reservoir eutrophication by increasing soil erosion and nutrient loads in runoff or through combined effects with other catchment and reservoir characteristics, causing changes in nitrogen and phosphorus ratios (Arbuckle and Downing, 2001; Knoll et al., 2003). Cyanobacterial bloom occurrences have been significantly correlated with measured levels of both total nitrogen and total phosphorus; occurrences of blooms in U.S. lakes and reservoirs include those with microcystin toxins frequently detected in the watersheds with the greatest agricultural influences (U.S. EPA, 2016; Marion et al., 2017; Zhang, 2020).

Leigh et al. (2010) assessed the vulnerability of reservoirs to water quality issues based on the physical characteristics of the catchment area. The authors were able to associate land use with water quality and described the effects of different reservoir volumes on catchment area ratios. Higher concentrations of chlorophyll and total phosphorus were linked to lower ratios of reservoir volume to catchment area (Leigh et al., 2010). Such ratios are more likely to have stronger links with land use of catchment areas and the resulting reduction in water quality (Burford et al., 2007; Leigh et al., 2010). Burford et al. (2007) found that watershed land use correlated with primary production, total phosphorus and chlorophyll, and that correlation was greatly improved when land use was combined with the ratio of watershed land area to reservoir volume. Generally, larger and highly altered watershed areas can contribute more nutrients per volume of the reservoir.

7.7 Review of Policy and Regulations

The following list of general policies is derived from Impact of Climate Change on Dams and Reservoirs, a document developed for the United Kingdom (Atkins 2013) that provides examples of climate change guidelines that could also be applied to dams in Canada:

- Incorporating climate change language into policy: Risk-based assessments should make specific reference to climate change in a way that links it to the existing statutory arrangements.
- Water demand and flood response: The majority of dam functions were found to be vulnerable to drier summers leading to lower water levels in reservoirs. Policy and regulation responses that aim to reduce demand are therefore helpful and important for reservoirs that are used for the seasonal storage of water. Similarly, the assessment of flood return periods and flood severity shows that climate change is likely to significantly increase the stress that is placed on existing flood storage reservoirs. Policies should promote sustainable drainage systems and the maintenance or reconnection of floodplains to reduce urban runoff.
- Water use and drought response: Climate change needs to be considered when policies relating to licensing, compensation flows and discharge consents are being reviewed. It should include consideration of how prioritization of water uses at times of climatic stress is controlled and implemented. Timescales involved in the implementation of drought response measures are particularly important since climate change can affect the nature of drought and water demand and, therefore, the speeds at which reservoirs are likely to empty. Reviews of the processes and legislation that surround drought response measures at reservoirs should consider the impact that the lead times involved in their application can have on the effectiveness of those measures.

- Ensuring sustainability of “green measures”: Green measures that are currently being designed into dams to improve their planning acceptability and environmental attributes often do not consider the implications of climate change. For example, green spillway designs may be vulnerable to climate change as they incorporate a thin topsoil cover on top of non-continuous concrete bases. It is recommended that policies and guidance should require that the sustainability of such designs in the face of climate change is considered alongside the usual drivers, such as biodiversity and landscape impacts.
- Catchment management and land use: Catchment management has been identified as a key factor in the potential impact mechanisms and constraints on dams and reservoirs. The effects of climate change need to be considered when land-use policies that might affect reservoir catchments are being developed. In particular, policies and initiatives that promote lower runoff erosion rates (e.g., lateral ploughing and maintenance of buffer strips) or provide advice on the adaptive capacity of various crop types recommend that reservoir catchments are identified as a specific concern when land-use policy and agricultural guidance is being developed by governmental organizations.

7.7.1 Possible Mitigation Strategies to Offset Climate Change Vulnerability of Dam Reservoirs

7.7.1.1 Retrofitting Outlets for Selective Withdrawal

In reservoirs that are stratified, multi-level outlets that draw water from different depths can be used to control the water quality of the reservoir and the downstream waters (USBR, 1987). For example, water withdrawn from the bottom of a dam (hypolimnion) will be cooler and will result in a warmer reservoir and cooler downstream environment, whereas water drawn from the surface of a dam (epilimnion) will be warmer and will result in a cooler reservoir and warmer downstream environment. Water from different depths can also be blended to create precise temperatures for release downstream and to control the temperature of the water left in the reservoir (USBR, 1987). Bottom withdrawals can also be used to flush nutrients out of the reservoir while preserving stratification layers (USBR, 1987). These types of multi-level outlets are ineffective, however, for reservoirs that are consistently well-mixed and do not stratify (e.g., wide, shallow reservoirs subject to wind action). Therefore, it is critical to understand the mixing patterns of a reservoir before considering whether it is a candidate for multi-level outlets.

7.7.1.2 Selective Withdrawal to Control Water Temperature

The flexibility to control temperature through selective withdrawal provides a way to thermally control the growth and productivity of biological communities. This can include artificially lowering temperatures in reservoirs to suppress the formation of algal blooms, but can also be a means to provide temperatures that support healthy populations of fish and invertebrates downstream of dams. For example, a temperature control device was installed on the Shasta Dam in the U.S. in 1997 to help improve thermal conditions for salmon downstream of the dam (Saito et al., 2001). Similarly, a dam in the South Fork McKenzie River was retrofitted to mix water from multiple depths before release in an effort to match downstream thermal regimes to the upstream environment (Murphy et al., 2021). In this case, however, they found that despite matching thermal regimes, the species composition of the downstream environment had more non-insect taxa and taxa known to feed on plankton and detritus compared with the upstream environment, which likely resulted from withdrawals from the epilimnion that increased the export of plankton and organic material. Similarly, Kolesar and Serio (2011) described an adaptive release framework developed for three dams on the Delaware River, which was created to increase the cold water habitat for trout and American shad while balancing the needs of New York City's water supply. To better control selective withdrawals, they developed a feedback system that employed a simple algorithm that prescribed conservation releases as a function of the amount of water in storage, which was based on performance measures including reservoir storage and refilled probabilities, drought-day risks, and the sizes of aquatic habitats by species, river segment and season (Kolesar and Serio, 2011).

7.7.1.3 Selective Withdrawal to Enhance Stability of Water Column to Control Nutrient Loading

Selective withdrawals from the bottom (hypolimnion) layer can be used to reduce the internal loading of phosphorus in reservoirs by preventing the development of deep anoxic layers (Marce et al., 2010; Bormans et al., 2016). Bottom withdrawals help stabilize the stratified layers of the water column, which reduces the availability of nutrients to the epilimnion and, therefore, can be used to limit cyanobacterial blooms (Bormans et al., 2016). Essentially, deep water withdrawals reduce the residence time of water in the bottom layers and also export nutrients, reduce substances and reduce organic material in the reservoir, which decreases the occurrence of conditions that promote water quality issues. Hypolimnion withdrawals are most effective when used during high summer internal phosphorus loading and before the water column begins to destratify in the fall (Bormans et al., 2016). Marce et al. (2010) showed how modeling can be used to simulate water quality scenarios to tailor the design of new dams, particularly in relation to the placement of withdrawal outlets at precise depths to minimize water quality problems. Retrofitting dams with selective withdrawal devices will be an important adaptive management tool to deal with the water quality issues that are exacerbated by climate change.

7.7.2 Vegetation and Green Infrastructure

Vegetation can be used to decrease shoreline erosion, control flooding and reduce runoff from terrestrial sources that can contribute to the nutrient loading of reservoirs (USBR, 1987). Examples of "green infrastructure" include constructed wetlands, healthy forest communities, bioshields and buffer zones constructed near reservoirs. In terms of overall water quality and flood control in the face of climate change, the use of grey infrastructure (dams) combined with green infrastructure is thought to produce synergistic results (Palmer et al., 2015). In a simulation of conservation practices under climate change scenarios in the Miyun Reservoir Watershed in China, runoff was reduced by 7–14% using constructed wetlands, grassed waterways, and 5–15 m vegetation filter strips separating the surface water from cropland (Qiu et al., 2020). Similarly, converting farmland to forestland over slopes of 15° and 25° reduced surface runoff by 6–7% by slowing water flow and storing and infiltrating runoff into the soil matrix (Qiu et al., 2020). When land cover in catchment areas is reforested, high water quality can be sustained for longer periods of time (Leigh et al., 2010). Further, forested watersheds typically export more dissolved organic nitrogen, which is less bioavailable, creating conditions less likely to directly contribute to algal growth (Burford et al., 2007). Watersheds with the largest natural cover show the highest capability to mitigate the impact of climate change (Danvi et al., 2018). Atkins (2013) also suggests planting riparian tree species along shorelines in order to provide shade, which reduces light levels and, therefore, algal blooms, and to break upwind, which causes water column mixing. Thus, catchment area management has been identified as a key factor in the potential impact mechanisms and constraints on dams, and the effects of climate change need to be considered when land-use policies that might affect reservoir catchments are being developed (Atkins, 2013).

7.7.3 Aeration and Deep Oxygen Injection

Artificial aeration has been shown to improve water quality by combatting the effects of eutrophication and anoxic conditions while maintaining thermal stratification (USBR 1987; Bormans et al., 2016). This introduction of surface air, and in some cases pure oxygen, to the hypolimnion, decreases sediment release and internal nutrient loading, in particular, ammonia and phosphorous (Beutel et al., 1999; Bormans et al., 2016). This strategy dates back to the 1970s and quickly spread to lake management across the globe, with some limited local success in Amisk Lake, Alberta (Beutel et al., 1999; Preece et al., 2019). While improving water quality and resulting in significantly lower levels of hypolimnetic ortho-P, ammonia and blue algae growth, full-scale oxygenation degraded the bottom of the metalimnion, causing it to decrease in thickness by an average of 1 m when compared to pre-treatment years (Beutel et al., 1999). More recently, this management strategy has become the most applied in-lake method to improve water quality in reservoirs (Gantzer et al., 2009). Aeration systems can be incorporated into the design of new dams or retrofitted into existing dams, however, the operating costs are high and the results of this strategy alone are not guaranteed and would benefit from being used in combination with other restoration methods (USBR 1987; Bormans et al., 2016; Preece et al., 2019).

7.7.4 Shade Covers

Shade covers are suspended screens or floating materials (shade balls) that are used to preserve water quality in reservoirs by reducing evaporation, reflecting UV rays and minimizing sunlight to suppress algal blooms, and shielding the water body from strong winds that induce mixing events (Martínez-Espinosa, 2021). Cloth shade covers are tarps that are suspended above the water surface by cables. Early studies on the effectiveness of shade covers show that they can reduce water evaporation by up to 85%, although the temperature of the surface water could increase, especially when using black covers (Martinez-Alvarez et al., 2010). Shade objects consist of individual hollow plastic spheres, squares or hexagons that float on the water's surface (Martínez-Espinosa, 2021). The shade objects are partially filled with water to avoid being blown by the wind thereby exposing the surface of the water to UV rays. A water reservoir in Spain was studied for two years after implementing shade covers and it was found that the reduction in solar radiation dramatically reduced the photosynthetic activity, thus limiting algal blooms (Martinez-Alvarez et al., 2010). Similarly, in 2015, 96 million shade balls were released into a water reservoir in California during a period of intense drought. By using the shade balls, it has been estimated that 300 million gallons of water is being conserved each year, while the shade balls block up to 95% of sunlight, which has had dramatic effects on reducing water quality issues (LADWP, 2016).

There is some controversy, however, surrounding the environmental impacts regarding the amount of water required to make plastic shade objects versus the benefits they have for reducing water loss and improving water quality (Erfan et al., 2018).

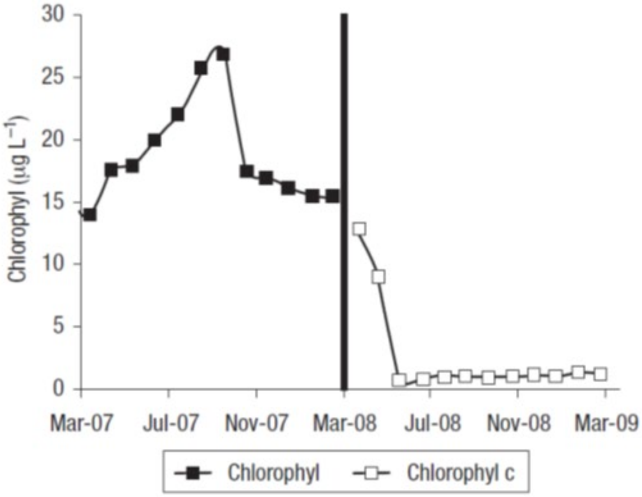

Figure 7.4 Average chlorophyll concentration profile for an uncovered (black squares) and covered (white squares) water reservoir (Martinez-Alvarez et al., 2010; figure licensed under CC BY 4.0)

7.7.5 Incorporating Climate Change Considerations When Building New Dams and Reservoirs

Mitigating climate-induced changes in water levels will likely involve increasing the number of dams to help control flooding and water supply storage. Therefore, climate change should be incorporated ad hoc into the design of these new dams and reservoirs. The following is a list of climate change considerations for constructing new reservoirs that was originally developed for the United Kingdom but could also be applied to Canadian systems (Atkins, 2013).

Adaptation of design standards for new reservoirs should include:

- Increased need for hydraulic capacity and useable flow to account for increased precipitation, additional silt and vegetation build-up in the reservoir.
- Review of vegetation type and soil cover specifications on the embankments, crest and spillways, with particular focus on resilience to hot weather, drought and sunlight exposure. The use of wildflower cover, grasscrete, swale type drainage or “wetland” dips on slopes should consider how periods of reduced precipitation or increased heat may affect their performance.
- Additional coverage of clay cores and clay materials to minimize desiccation risks.
- Review of the use of materials susceptible to heat and UV damage, such as high-density polyethylene, geotextiles and liners.

- Review of the materials and construction techniques that may be affected by increased temperatures, such as the type of fill used for joints and its expansion capability, grass cover specifications and liners.
- Review of catchment-related issues. Consideration of the effect that changes in catchment erosion rates, vegetation type and vegetation health may have on drainage, water quality, monitoring and maintenance needs.
- Consideration of the use of appropriate concrete specifications to suit projected local climatic conditions, in particular the impact of UV radiation and increased temperatures.

7.8 Methodological Approaches for Evaluation of Climate Change Impacts on Dam Water Quality

Water quality assessment in reservoirs is of essential importance for efficient and appropriate management of the water quality in the reservoir and downstream. Reservoir water quality modeling can provide a useful tool that augments the monitoring information for water quality assessment and prediction of future changes in reservoir water quality. Various mathematical models such as CE-QUAL-W2, MIKE, WASP and EFDC have been implemented in the literature in order to simulate the water quality in reservoirs. Each of these models has its own capabilities and limitations. The outcome of such models can be integrated with future climatic conditions and help decision makers better understand reservoir water quality under climate change.

7.8.1 Numerical Modeling and Data

A methodological approach for the evaluation of climate change impacts on dam water quality will require several models to be appropriately integrated into one framework: (1) a water quality model that is capable of representing the required water quality processes; (2) an air-water interaction model to adequately represent the interactions between the ambient climatic conditions (e.g., temperature, wind, sunshine, etc.) to simulate water temperature and ice conditions; (3) a hydrodynamic model that can simulate the flow processes that are required for the representation of transport processes; and (4) climate model outputs to provide the required ambient climatic conditions under various future climate scenarios.

7.9 Results and Recommendations

Climatic changes that are expected to increase in frequency and intensity have been found to have varying impacts on reservoir water quality, and certain characteristics of these reservoirs are highlighted as having an increased vulnerability to climate change. For example, increased precipitation could introduce a higher abundance of nutrients and sediments from catchment areas, especially those that have been developed for anthropogenic activities, and can affect water quality through the occurrence of algal blooms, increased turbidity and the destabilization of the water column, particularly in small-sized reservoirs. Extreme wind events are expected to increase internal nutrient loading and turbidity by increasing resuspension; this will have the greatest effect on reservoirs with a high surface area to volume ratio (i.e., shallow reservoirs). Wind events are also expected to deepen the hypolimnion, affecting water column stability. As air temperatures increase, water temperatures will also increase, which will create more stable water column stratification and lengthen the time that anoxic conditions occur in deeper layers, thereby releasing nutrients such as phosphorus from sediment. In these cases, the anoxic conditions can be exacerbated by the age of the dam, where new dams have high amounts of organic matter available for decomposition and older dams have longer residence times and stratification periods. Temperature change will also impact freeze-thaw cycles and create preferable conditions for algal blooms.

Proposed methods to mitigate water quality issues that relate to climate change parameters are as follows:

(1) Selective withdrawal: Allows for temperature control of reservoir and downstream waters to compensate for changes in surface water temperature, reduces internal nutrient loading, increases water column stability, and reduces the formation of deep anoxic layers.
(2) Increasing vegetation and re-naturalizing shorelines: Reduces runoff (external nutrient loading) that promotes algal blooms, reduces shoreline erosion and reduces sedimentation and turbidity.
(3) Aeration and deep oxygen injection: Decreases internal nutrient loading by preventing the formation of deep anoxic layers and stabilizing the water column.
(4) Shade covers: Reduces light levels to suppress algal blooms and shields reservoirs from wind events that induce water column mixing.

Table 7.2 Relation of water quality issues to climate change events and dam characteristics

Water Quality Issue	Climate/Weather Causal Event	Dam Characteristics Likely to Increase Vulnerability
Increased Nutrient Loading	• Rain: External nutrient loading through runoff • Drought: Increase concentration in reservoirs with little external loading; decrease concentration in reservoirs with high external loading • Wind: Resuspension of nutrients from sediments through mixing • Temperature: Can shift the timing of snowmelt and freezing	• Catchment area development: Agricultural and urban development in catchment areas can exacerbated the increase of external nutrient loading • Reservoirs with a higher watershed area to lake surface area ratio are more prone to changes to external nutrient loading • Lakes with higher fetch will be more prone to wind-related effects (including resuspension)
Increased Water Column Stability (Stratification)	• Temperature: Heating the surface waters can create a steeper gradient in the metalimnion creating higher stability (more intense stratification)	• Larger reservoirs (by volume) will have longer residence times allowing for greater heating of surface waters, leading to increases in stability (prolonged period of stratification); this is a particular risk for reservoirs where decomposition can promote anoxic conditions in the hypolimnion
Decreased Water Column Stability	• Wind: Deepening of mixed surface layer can lessen stability and lead to upwelling • Drought: Decreased depth can lead to increased mixing (less stability)	• Shallow, stratified reservoirs are more prone to wind destabilization
Increased Turbidity	• Wind: Increase turbidity through resuspension of particulates • Rain: Increased runoff can carry more particulates from catchment area • Drought: In reservoirs with a high amount of turbidity from runoff, drought can reduce turbidity by slowing inputs; in shallow reservoirs lower water levels due to drought can make the reservoir more prone to resuspension of particulates by wind	• Agricultural and urban development within a catchment area is associated with higher turbidity in tributaries • Reservoirs with a large surface area are more prone to resuspension by wind action; this is especially true for shallower reservoirs • Vegetation along the shoreline (both aquatic and terrestrial) can reduce the amount of resuspension by wind • The type and texture of the substrate can also greatly influence the amount of resuspension

Table 7.2 (continued)

Water Quality Issue	Climate/Weather Causal Event	Dam Characteristics Likely to Increase Vulnerability
Algal Blooms	• Rain: Increased runoff can lead to higher nutrient concentrations creating appropriate conditions for algal blooms • Increased temperature: Can cause a shift in inputs from snowmelt, potentially favoring algal growth over macrophyte growth • Wind: Increased resuspension can lead to favorable conditions for free-floating algae, while also limiting the availability of light for macrophytes • Drought: Reduced water levels could potentially lead to increased concentrations of nutrients	• Catchment area development can lead to increased nutrient concentrations, which could promote algal blooms • Large reservoirs will have longer residence times allowing for greater heating of surface waters, leading to increased duration and intensity of stratification, which could promote algal blooms • Small reservoirs with high watershed to lake surface area ratios are more prone to increased concentrations of nutrients during rainfall events, which could lead to algal blooms
Anoxia	• Increased temperature: Can lead to strengthened stratification, which can lead to anoxia within the hypolimnion	• Deep, stratified reservoirs are most likely to experience anoxia; newly constructed lakes (< 10 years old) are more prone to anoxia based on high levels of decomposition
Fish Habitat	• Wind: Wave action and increased turbidity can reduce the amount of macrophytes along a shoreline, reducing the amount of suitable fish habitat • Temperature: Fish are sensitive to increasing temperature; increases in extreme heat due to climate change could reduce the fish habitat	• Lack of multi-level outlets: Water being withdrawn from one level (in a stratified reservoir) can influence the temperature both within the reservoir and downstream of the dam
Surface Temperature	• Air temperature: Can directly affect surface water temperatures • Wind: Can cause a deepening of the epilimnion resulting in cooler surface waters; upwelling and downwelling caused by wind can also influence surface temperatures	

7.10 Gap Analysis, Future Directions and Workshop Feedback

7.10.1 Identified Gaps

(1) Changes in frequency and intensity of various climatic variables under climate change, such as temperature, precipitation and wind, were shown to have varying impacts on dam reservoir water quality, while certain characteristics of these reservoirs are highlighted as having an increased vulnerability to climate change. The impacts of climate change on the water quality of dam reservoirs depends on several factors, including the reservoir and watershed characteristics. Understanding the impacts of climate change on water quality in dam reservoirs can provide insights into the management and operation of dams.

(2) Climate change impacts on water quality in dam reservoirs can have crucial implications for aquatic habitats both in the reservoir and downstream. Fish habitat suitability is of essential importance for several stakeholders and communities. Climate-induced changes in water temperature can impact the suitability of fish habitats both within the dam reservoir and downstream. The thermal profiles of nearshore environments are particularly important because they are the site of physiological activities that occur within specific temperature ranges, such as spawning, egg development and young-of-the-year growth. Nearshore fish habitats located close to dams may be subjected to fine-scale temperature changes resulting from peaking and ponding that exaggerate the overall climate-induced temperature changes found in the main stem of the river. Understanding the relationship between the main stem water temperature and the fine-scale temperature of nearshore habitats can provide insights into how the management and operation of dams may be used as a tool for mitigating the effects of climate change.

7.10.2 Future Directions

The projects below are being considered in order to address the identified gaps above:

(1) Climate change impacts on water quality in dam reservoirs: In order to respond to gap (1) above, it is proposed that an appropriate dam reservoir be selected for the development of an integrated water quality model. The developed model could be a useful tool for the assessment of climate change impacts on water quality in dam reservoirs under various future climatic scenarios. The results of the model can be extended to other reservoirs based on the physical characteristics of reservoirs and watershed characteristics. Further details of this proposed project are outlined in Appendix A.3.1.

(2) Development of fish habitat model considering climate change impacts: In order to address gap (2) above, it is proposed that a fish habitat model is developed for the St. Lawrence River. A model will be developed using artificial intelligence to estimate the water temperature based on ambient climatic variables and hydrodynamic conditions. The results of the model will be tested against empirical temperature data collected using water samplers installed at the intake of dams and continuous temperature loggers placed in nearshore environments. The model would involve two components: (1) large-scale

temporal temperature changes, and (2) smaller-scale temperature changes caused by peaking and ponding. Predictive temperatures will be compared to existing information on the thermal requirements for reproduction and growth of multiple fish species living in the St. Lawrence River. Further details of the proposed project are outlined in Appendix A.3.2.

7.10.3 Workshop Feedback

In the online input platform, the suggestion was made to make the future work applicable to a broader context by considering which aspects of water quality are vulnerable to climate change and what future scenarios would lead to the greatest impacts on reservoir characteristics. More details can be found in Appendix B.

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8 Monitoring Methods for Continuous Dam Operations

8.1 Introduction

Generally, dam failure is always catastrophic and associated with intolerable fatalities and significant economic loss (e.g., major disasters at Malpasset (France, 1959), Vaiont (Italy, 1963), Teton (USA, 1976), and Macchu II (India, 1979)). However, other than a failure resulting from a direct extreme flood event, a fairly long period of escalating structural distress within the dam and/or its foundation usually precedes any dam failure (Novak et al., 2007). Therefore, dam surveillance and instrumentation programs are implemented to detect distress symptoms and prevent possible dangerous defects at the earliest stages (e.g., significant settlements or displacements, sliding, cracks, or considerable amounts of seepage water). Furthermore, the ongoing adverse effects of climate change on dams increased the pressure on dam owners to ensure the safety of these massive structures (Rezatec, 2021). Thus, efficient health monitoring, commonly referred to as dam surveillance, has become increasingly important to preserve the stability and structural integrity of existing dams.

Instruments are strategically installed within or on a dam to detect behavioural abnormalities and provide early warning signs of the potential to develop a serious incident or failure. Multiple factors control the effectiveness of dam instrumentations, including selecting the correct equipment, adequate installation, choosing the right locations, and intelligent interpretation of data. The numbers of instruments installed are of no value if these factors are not met (Novak et al., 2007).

The main objectives of this section are to:

(1) Outline the traditional and most recent instrumentation techniques adopted in dam monitoring.
(2) Identify research gaps and specify the most effective monitoring technologies for dam applications.
(3) Outline a research plan for the coming years to investigate the reliability of the results determined by the technology selected when used in practice.

8.2 Monitoring, Instrumentation and Measurement

The observations made by the instruments that provide data related to dam performance and behavioural trends and the recording of this data is referred to as monitoring (Tanchev, 2014). New dams of any size are typically built with monitoring instruments. Instrumentation data are interpreted to confirm the validity of the design and initial assumptions based on predicted dam performance. On the other hand, for existing dams that do not have such instruments, it is good practice to upgrade them with basic instrumentation. For these dams, instruments may be applied to assess dam safety and detect any unexpected deviations in the expected behaviour of the dam over the long term. Moreover, instruments may be required to report on parameters related to faults in the design or related damage that develops later (Novak et al., 2007).

Based on their main function, monitoring instruments can be categorized into:

(1) Construction control: Used to verify critical design parameters and provide immediate feedback on design and construction.
(2) Post-construction performance: Used for design validation and the determination of behavioural patterns.
(3) Service performance/surveillance: Used to provide a measure of reassurance and structural adequacy, and to detect regressive change in behavioural patterns and identify suspected problems.
(4) Research/development: Used for academic research and equipment development.

8.2.1 Monitoring Parameters

The main parameters for monitoring dam behaviour are listed below (Tanchev, 2014):

(1) The quantity, nature, location and source of seepage and leakage.
(2) The magnitude and rate of settlement and loss of freeboard in embankments.
(3) The magnitude, rate and location of external and internal deformations.
(4) The magnitude and variation of porewater pressures and uplift.

While specific parameters such as seepage and deflection are of primary concern for all types of dams, other parameters such as porewater pressures are only of concern for earthfill dams. For example, seepage under hydraulic structures, including concrete dams, is considered to be a dangerous phenomenon that may lead to structural collapse if neglected (Saleh, 2018).

Minimum monitoring in all dams should include the measurement of seepage flows and crest deformations. Monitoring crest deformations is essential in detecting possible internal distress and local loss of the freeboard, which is the vertical distance between the crest of the embankment and the surface of the reservoir water (Novak et al. 2007). Seepage flow should be monitored regularly and detected in all large dams, since observing any change in the seepage regime through or under the dam indicates that serious problems could follow. It is relatively simple to directly observe seepage volume by setting several weirs to collect the flow from specific lengths of the dam. With this approach, any change in the seepage regime can be readily identified for approximate locations (Novak et al., 2007; Tanchev, 2014).

The key parameters that are usually monitored for embankment and concrete dams, including their foundations, are summarized in Table 8.1 (ICOLD, 2018).

Table 8.1 Main dam monitoring parameters (ICOLD 2018)

Concrete Dam	Embankment Dam	Foundations
Structural deformations	Deformations of dam body	Deformations Abutment movements
Special movements (cracks, joints)	Special displacements (links with a concrete structure)	Special displacements (cracks, diaclases)
Dam body temperature	Dam body temperature to detect seepage (possible)	Dam body temperature to detect seepage (possible)
Uplift pressures (contact in concrete-foundation and in the rock)	Pore pressures in embankment dam body and piezometric level	Pore pressures Deep body uplift pressure Piezometric level Phreatic line level
Seepage and drainage rates	Seepage and drainage rates	Seepage and drainage rates and resurgences (sources)
Chemical analysis of seepage water Turbidity (possible)	Chemical analysis of seepage water Turbidity	Chemical analysis of seepage water Turbidity

8.2.2 Instrumentation Planning and Design

Any dam instrumentation program includes the selection of required instruments, installation instructions, commissioning, monitoring, data management software and data interpretation.

In the instrumentation planning stage, the following logical sequence of decisions must be considered (Novak et al., 2007):

(1) Definition of the key purposes and objectives.
(2) Definition of observations suitable to the dam.
(3) Identification of the critical locations and number of measurements required.
(4) Specifying the time period for the observation (i.e., long- or short-term monitoring).
(5) Selection of optimum sensing mode, desired rapidity, required accuracy, etc.
(6) Proper selection of suitable hardware for monitoring.

The monitoring equipment is selected based on the measuring range required, and all instruments should be selected and planned to operate satisfactorily for several decades and under very harsh environmental conditions. Therefore, in the design stage, the following should be considered (ICOLD, 1989; Tanchev, 2014; ASCE, 2018; ICOLD, 2018):

(1) Instruments should be simple in concept and easy to operate.
(2) Only reliable and robust instrumentation suites should be selected.
(3) Durability under harsh environmental and operating conditions is required.
(4) Dam instrumentation should be cost-effective; this includes initial purchase, installation, operation and maintenance.

In recent years, instrument capabilities have witnessed significant developments and reliable and robust tools are currently available. Automation and the capacity for storage and the transmission of data to a central location are also being integrated. Nevertheless, the superior capabilities of these sensors are always associated with high costs, complexity, and a higher risk of malfunction and failure. Therefore, relatively basic instrumentation is used in most dams with successful results, and using sophisticated and expensive instruments can only be justified in exceptional circumstances (ASCE, 2018).

Although dam monitoring always covers critical locations, points of normal behaviour are also sometimes monitored for comparison. Typically, an ideal instrumentation plan is first drafted, and then the less essential provisions are progressively disregarded. The final plan must be suitable, practical and cost effective. Success mainly depends on giving attention to details during the installation and data-handling stages.

The initial impounding and the first few years of the dam's life represent the most critical stage in new construction. This is because the dam and the foundation progressively adjust to the loads applied. In general, any weaknesses in design or construction will appear at this early stage. Therefore, the initial impounding should occur at a controlled and moderate rate if dam and foundation responses are closely monitored during this stage and for the critical few years that follow. As a matter of fact, the instrumentation level in embankment dams is more comprehensive and complex than in concrete dams of the same size (Tanchev, 2014).

In general, a moderate level of instrumentation is provided in new dams as the risk of failure of these dams is relatively low. The minimum monitoring requirement should include tracking the seepage flow through the internal drainage system and measuring the settlement of selected stations, which are usually spaced at 20 m or 25 m along the crest of the embankment dam. Instrumentation may also be indispensable for small dams (e.g., farm or amenity dams) if they present a possible hazard in the event of breaching.

Currently, the retrospective installation of instruments on existing, un-instrumented dams is common practice for existing embankments that represent a significant potential hazard. Minimum retrospective instrumentation should always include the monitoring of seepage flows and crest settlement. However, in certain cases, further monitoring of local piezometric and/or deformation profiles through the body of the embankment may also be considered.

8.3 Conventional Dam Monitoring Technologies

Various conventional instrumentation suites have been used and implemented for several decades to monitor and obtain data on the behaviour of dams and their foundations during construction, reservoir filling and operation. These instruments are used extensively to measure strain, temperature, stress, deflection, deformation, contraction joint opening and porewater pressure of the dam. The information obtained from dam monitoring is of high importance for assessing the safety of the structure during construction and operation, as well as for future design and development. Based on the data collected from the monitoring process, appropriate steps can be taken to overcome problems that may arise (Tanchev, 2014). A brief description of the more common instruments used in dam monitoring is given in Subsections 8.3.1 to 8.3.5.

8.3.1 Settlement and Displacement at the Surface of the Dam

Traditional surveying methods such as optical and electronic distance measuring instruments are adopted to measure the relative vertical and horizontal movements of specific locations at the dam surface. Levelling is also used to check the crest alignment of concrete dams and can be accompanied by tilt data from pendula installed in internal shafts and inverted floating pendula anchored in deep boreholes in rock foundations. Relative movement within the body of the dam can be measured by simple mechanical or optical joint meters. Finally, earthfill dam deformation is usually obtained using sensitive borehole inclinometers to establish the internal horizontal displacement profiles through the height of a dam (Novak et al., 2007; ASCE, 2018).

There are limitations to traditional surveying methods during winters in Canada, where dams located in remote areas could be inaccessible to the working crew or require significant effort to reach the dam location and conduct the survey safely.

8.3.2 Porewater Pressure

Porewater pressure measurements are essential for assessing the stability of earthfill dams, the potential conditions in foundations, and the identification of unusual seepage pressure (Tanchev, 2014). Piezometers are used to determine the porewater pressure in the body, abutments and foundation of the dam. The three primary types of widely applied piezometers are hydraulic, electrical and pneumatic. Piezometers are installed in previously made boreholes. Occasionally, piezometers are provided during the construction process. The locations of these instruments should be carefully planned and selected to provide complete information on the intensity and distribution of porewater pressure. In embankment dams, there are usually several rows of piezometers that are transversely installed, starting from the upstream edge of the crest down to the downstream toe (Novak et al., 2007).

8.3.3 Settlement and Deformation in the Interior of the Dam

For low-height dams, only the surface displacements are measured using the monitoring program. However, it is obligatory to monitor deformations in the interior of medium- and high-height dams in addition to surface displacements.

During the construction process of earthfill dams, vertical tube extensometer gauges with external annular plate magnet measuring stations are securely placed at vertical intervals of 3.0 m. These devices are used to precisely detect relative levels and increments of internal settlement. On the other hand, spider-type magnet stations are installed in boreholes at suitable intervals for existing embankments and foundations.

Horizontal internal deformation is monitored using a borehole inclinometer or vertical extensometer gauge. Vertical extensometer gauges are installed in trenches within the shoulder fill at suitable horizontal intervals.

Inclinometers (i.e., borehole instruments) used for measuring strain profiles in soil, rock and concrete structural elements were first developed in 1970 at the Federal Institute of Technology, Zurich, Switzerland. Since then, inclinometers have been effectively applied to different engineering projects (ICOLD, 2018). This system consists of measuring casings installed inside boreholes located in the body of the earth dam. Each measuring casing includes a series of reference points spaced at 1.0 m. The strains and deformations of the earth can then be detected by the inclinometer, which measures the relative displacements of adjacent reference points. Results obtained with this measuring system are highly accurate (ASCE, 2018).

Usually, arch dams are provided with fixed-length rock extensometers to monitor the response of their abutments. These extensometers could also be used in concrete dams to detect any deformation of the foundation.

8.3.4 Internal Stress

To measure internal stress, an oil-filled metal disc connected to a pressure transducer that responds to fluid pressure as a function of the external stress applied on the face of the disc is installed in concrete and rock. Alternative instruments such as hollow disc earth pressure cells are sometimes used in embankment dams to serve the same purpose. The stress can be predicted indirectly by measuring the strains, however, severe difficulties could be encountered using this approach due to the nonlinear and time-dependent stress-strain response. These uncertainties could result in collected data that is less meaningful. Therefore, field instrumentation for this purpose is not always recommended and is generally only associated with research projects (Novak et al., 2007).

8.3.5 Leakage and Seepage

It is essential to regularly investigate suspected leakage positions and track seepage paths within the embankment dam and throughout its foundation. Piezometers may be used for this purpose when the situation is not deemed urgent and time allows for a planned investigation. For cases when time is considered critical, and provided that approximate locations of a suspected seepage path are difficult to identify, fluorescein dyes or radioactive tracers can be employed to locate the entrance and exit points of seepage and track the seepage path (Novak et al., 2007; Tanchev, 2014).

8.4 Recent Dam Monitoring Technologies

Extensive research has been carried out to develop novel monitoring technologies for dams (ICOLD, 2018). The ability of dam monitoring has been enhanced in different ways by these recent developments in instrumentation approaches and recently, a number of these technologies have been applied successfully. For example, better data evaluation is now possible due to the improved accuracy provided by the recent techniques and these improvements in data evaluation have expanded the understanding of the physics of the data measured.

Some of the most recent dam monitoring technologies that have been effectively applied in research projects and in practice are reviewed in Subsections 8.4.1 to 8.4.9.

8.4.1 Fiber Optic Sensing

Generally, low-seepage flow regions of the dam have a different temperature distribution than high-seepage flow regions. Therefore, the locations and quantity of seepage flow in dams and their foundations can be indirectly determined through the use of temperature measurements. Temperature values with accuracies of ± 0.1°C can be measured by installing a protected fiber optic cable in the required sections of the dam. These cables are highly durable, therefore, cable failure under normal operating conditions is unexpected. Moist, partially saturated or fully saturated medium can be detected through the response of the cables to the thermal surroundings.

Similarly, this approach can also monitor the strains at intervals of 1 m over long distances (i.e., distributed sensing). Thus, the fiber optic cables make strain sensing of an entire dam possible. Local dam movements can also be measured at the early stages using this technique. Notably, the additional information provided by using this technique could be helpful by comparing it with the data collected using traditional surveying methods (Tanchev, 2014; ASCE, 2018; ICOLD, 2018).

To date, a cost-effective fiber-optic system for dam monitoring has been slow to develop; therefore, similar parameters can be monitored by other lower-cost technologies. Furthermore, installing long, brittle fiber-optic cables could be impractical and can obstruct the construction process, while it is also possible to lose measurement data due to an accidental severing of the cables. That being said, it is expected that dam monitoring using fiber-optic cables will be used more frequently in the future due to the continuing reduction in the cost of this technology. The accumulation of measurement data using this approach could lead to a better understanding of dam behaviour and to improved predictions (ASCE, 2018).

8.4.2 Bathymetric Multi-Beam Sonar

A multi-beam sonar instrument is often installed on a remotely operated water vessel to scan a relatively extensive area within a short period using a high-resolution echo sounder. This system allows for the recording of hundreds of data points simultaneously as the vessel scans specified lines over an accurate location. A GPS point on the shore and inertial measurement units collect information simultaneously with sonar scanning (Isomäki and Hänninen, 2015). Using specialty software, the data is processed and combined to form a 3D image of the dam or a plan with section views for immediate engineering use. The application of multi-beam scanning in structure monitoring has increased due to its efficiency in the field and although the cost of this technique is higher than traditional methods, its widespread use could eventually reduce costs overall (ICOLD, 2018).

Multi-beam bathymetry offers the possibility to assess the condition of the in-water parts of concrete dams and measure the cavities in embankment dams. However, water turbulence decreases the sensitivity of this monitoring technique and the resolution could potentially be reduced (ICOLD, 2018).

8.4.3 Unmanned Aerial Vehicles (Drones)

Unmanned aerial vehicles (UAVs) are remotely piloted aircraft that can fly autonomously either by using an onboard computer system or a remote (Figure 8.1). The UAVs can be employed to visualize, monitor and analyze infrastructure such as dams by taking high-resolution photographs and videos (Duque et al., 2018). Large areas that are inaccessible or unsafe can be examined with ease, and large dams can be measured quickly using this technology. This feature is essential when an emergency inspection of a dam and its appurtenant structures is required (ASCE, 2018). Particular types of underwater UAVs also allow for monitoring of the submerged dam surface (Figure 8.2). In addition to maximizing the efficiency and effectiveness of dam monitoring when using underwater drones, safety is always ensured.

Figure 8.1 Monitoring using UAV
(iStock.com/seregalsv)

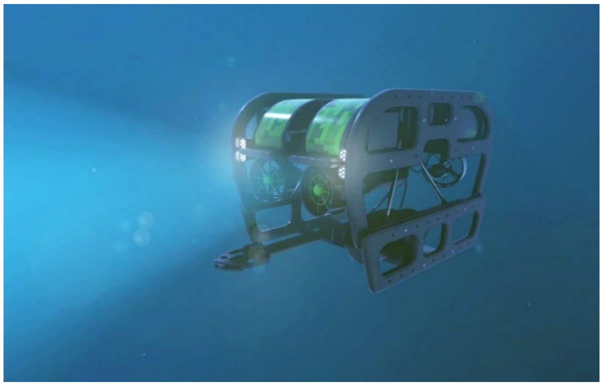

Figure 8.2 Remotely controlled underwater drone
(iStock.com/3dsam79)

8.4.4 Global Navigation Satellite System (GNSS)

The recently developed Global Navigation Satellite System (GNSS) appears promising for dam monitoring because the Continuously Operated Reference Stations are now being implemented on a larger scale worldwide. Positioning in the GNSS is accomplished by measuring the distances between a receiving antenna and not less than four orbiting satellites. Both the horizontal and vertical displacement readings of dams determined by this system have been compared with corresponding readings obtained by geodetic surveying methods, and the differences between the two approaches are negligible. Therefore, the GNSS is very effective at monitoring displacements in large dams. In addition, the GNSS allows for the measurement of baselines between non-inter-visible stations and can reasonably function in unfavourable weather conditions; features that are not applicable to conventional surveying methods. As long as clear sky conditions exist, the GNSS seems to be competitive with traditional approaches for measuring displacements in terms of accuracy, robustness and cost.

8.4.5 Terrestrial Laser Scanning

Terrestrial laser scanning technology, also called light detection and ranging (aka LiDAR), is used to obtain reliable data remotely and with satisfactory quality by generating a 3D model of the dam site. With this technology, a laser is used to scan the profile of the dam and the reflected light is analyzed to determine distances between the laser scanner and the dam resulting in high-resolution, three-dimensional digital maps and terrain models. Information about the geological condition of the foundation, condition of the entire dam, downstream stability, abutments, appurtenant structures, and retaining works during the operation stage can be predicted by laser scanning technology. Moreover, deformation and dimensional displacement data are also measurable. Finally, the information reported during visual inspections can be codified into an electronic database. Nevertheless, hardware, software and methodology developments related to laser scanning and digital imagery are ongoing.

8.4.6 Ground-Based Interferometric Synthetic Aperture Radar

Using ground-based interferometric synthetic aperture radar (GBInSAR) technology, the dam is monitored using radar interferometry ground stations located in front of the dam structure. Movements of points in the line of sight are measured with an accuracy of ± 0.1 mm. In 2006, the GBInSAR approach was used to measure the horizontal displacements in the downstream and upstream directions of Venina Dam in Italy (multi-arch concrete dam). The measurements collected were compared with the corresponding measurements taken by traditional surveying methods and it was determined that the GBInSAR technology corresponded to a precision of ± 0.4 mm (ICOLD, 2018).

Unlike traditional monitoring methods, accessing the area to be measured is not required when using GBInSAR and targets as far as 1.0 km can be measured, while this technique also allows for night-time monitoring. Finally, displacement maps for the entire dam can be produced. However, snow and vegetation could cause signal disturbances in the winter and summer seasons, respectively. GBInSAR is only suitable for providing displacement measurements of small areas in the short term, while spaceborne interferometric synthetic aperture radar (InSAR), described in the next subsection, is a powerful remote sensing technology for surveying large areas (Pieraccini and Miccinesi, 2019).

8.4.7 Spaceborne InSAR

In the past, spaceborne InSAR was mainly used for detecting the subsidence of large areas or post-earthquake-related deformations. Lately, the use of differential InSAR (DInSAR) and persistent-scatterer InSAR (PS-InSAR) techniques in dam monitoring has increased due to the significant development witnessed in the processing technologies and repeat pass times. This has enabled the collection of deformation data with high accuracy and high resolution for several ground structures (Scaioni et al., 2018). Displacement measurements for the required target are taken by a sensor installed on a satellite (Figure 8.3), which can provide data at night and even in cloudy weather. Vertical displacements can be determined with accuracies of up to ± 1.0 mm. Satellites repeat their passes over a specific target using the same viewing geometry approximately every week or month depending on the satellite mission. For some satellite missions, images are currently available for the past thirty years, making it possible to obtain historical movement data from archived images (ICOLD, 2018). This useful feature facilitates the monitoring of precursor movements that might result in hazardous situations (e.g., dam slope instability).

Figure 8.3 SAR Monitoring Technology (iStock.com/aapsky)

8.4.8 Ground Penetrating Radar

Ground Penetrating Radar (GPR) is a shallow distance geophysics survey technique, where two electromagnetic waves develop a radargram image of the underground using a signal-transmitting antenna and a receiving antenna. With the GPR technique, a large portion of the dam interior can be detected quickly without the use of destructive sampling (Loperte et al., 2011). GPR is used as a non-destructive technique to investigate the condition of the upper part of the core of embankment dams by slowly moving the two antennas along the dam axis. The distance between the two antennas is kept constant during this survey. Any change in the arrival time and energy of electromagnetic signals reflected from the media is an indication that disturbances have already occurred further down in the core.

The GPR approach is cost effective since a 2–3 km survey can be completed in one hour, and the data obtained can be interpreted in the field without further data processing (ICOLD, 2018).

8.4.9 Resistivity Measurements

In the resistivity method, useful information about the dam condition can be collected by introducing an electrical current into the ground and measuring the resulting potential distribution. The electrical resistivity of soils and rocks is affected by the clay content, groundwater conductivity, porosity and degree of water saturation. Therefore, seepage, embankment status and defects can be predicted easily. Internal erosion can also be identified through resistivity measurements since the material structure can change due to the washout of fines (Sjödahl et al., 2005).

Resistivity surveys can be applied once to detect abnormal sections along the dam and identify structurally weak spots, while long-term resistivity surveys can be performed to monitor seepage-induced seasonal variation in earthfill dams and to detect fluctuations over time for specific locations. Although long-term resistivity surveys are more powerful in offering additional evaluation potentials for seepage analysis, this approach is also more demanding in terms of instrumentation and observations.

The application of the resistivity method can be challenging in dam monitoring, and in order to attain the required accuracy, substantial efforts must be made. Complex dam geometry, noise sources and reservoir level fluctuations can all impede the interpretation of data (ICOLD, 2018).

8.5 Current Monitoring Guidelines

In almost every country in the world, dams are monitored by their owners and/or operators. Many countries have agencies that set guidelines and regulations for dam monitoring. The following is a list of some of these agencies (ASCE, 2018):

1. Canadian Dam Association (CDA);
2. Central Water Commission (CWC) in India;
3. U.S. Federal Energy Regulatory Commission (FERC);
4. China Ministry of Energy;
5. The Environment Agency in England and Wales;
6. Frances Permanent Technical Committee; and
7. Australian National Committee on Large Dams Incorporated (ANCOLD).

In Canada, the Surveillance of Dam Facilities document, issued in 2007 by the CDA, is used as a guideline for dam monitoring (CDA, 2013). According to this document, surveillance of dam facilities includes both visual inspection and monitoring of any installed instrumentation. While not providing specific prescriptive requirements, the CDA guidelines on dam safety provide overarching principles for dam surveillance. The main principle reads as follows: “Effective dam surveillance is to be based on an understanding of how the dam might fail (failure modes), what early signs of failure to look for, and what inspection or monitoring measures could be used to detect a developing failure.”

The CDA guidelines stipulate that the surveillance program should provide regular monitoring of dam performance, such as:

- Comparing actual and design performance to identify deviations;
- Detecting changes in performance or the development of hazardous conditions;
- Confirming that reservoir operations are in compliance with dam safety requirements; and
- Confirming that adequate maintenance is being carried out.

Regarding the frequency of scheduled inspection and monitoring activities, the guidelines state that their frequency should reflect the consequences of dam failure, dam condition and past performance, rapidity of development of potential failure modes, access constraints due to weather conditions, regulatory requirements, security needs, and other factors. The CDA also recommends performing special inspections after the occurrence of unusual events, such as earthquakes, floods or rapid drawdown. Instrumentation is not mandatory but the guidelines say that it may be necessary depending on the consequences of dam failure and on the need to understand the performance parameters that should be measured quantitatively. When follow-up actions are required, it is suggested that such actions might range from continued or enhanced inspection and monitoring, to remedial repairs and upgrading of the dam system.

8.6 Gap Analysis, Future Directions and Workshop Feedback

Dam health monitoring is indispensable for ensuring dam safety conditions and maintaining operational functions during the service life of the dam. Due to dam complexity, a manifold of instruments must be installed to achieve an adequate monitoring strategy. Since the failure event of a dam represents a high risk to the people settling downstream and the surrounding environment, careful surveillance becomes essential to detect anomalous behaviour and prevent any critical situation from developing.

8.6.1 Identified Gaps

In this section, traditional and recent dam monitoring techniques were briefly described. It can be noted that for decades, conventional dam monitoring methods, including deformation, geotechnical, hydraulic and structural sensors, have been successfully applied. However, research is still ongoing to improve data processing and the calibration techniques used.

(1) Regular monitoring of the crest deformations for dams is essential in detecting possible internal distress. Nevertheless, it is sometimes impossible to regularly access dams in remote areas to measure deformation using traditional surveying methods, particularly in winter. The current advancement in remote sensing technologies could provide an excellent solution to this challenge. However, minimal research has been conducted to verify the applicability of this approach in dam monitoring.

(2) Dams are massive structures and many different factors can affect their stability, making their health monitoring often complex and requiring an integrated monitoring system (IMS). Available literature lacks examples of IMS related to dam monitoring (Scaioni et al., 2018).

8.6.2 Future Directions

The following projects are considered to address the identified gaps:

(1) Satellite-based monitoring of dams: In order to address gap (1) above, extensive research should be carried out at the National Research Council Canada (NRC) that focuses on the application of InSAR as a monitoring technique for determining dam displacements, including those resulting from the effects of climate change (e.g., higher average temperatures, increased temperature extremes, higher pressure on dams due to severe flooding, etc.). This research will be used to confirm the reliability of this approach and increase its use in practice. Many dams are located in remote regional areas of Canada

and are hardly accessible for traditional surveying crews in winter, a factor that could become worse due to permafrost melting under climate change. Instead, the InSAR technique offers a practical solution to this problem. Furthermore, the NRC has the required expertise and personnel to conduct research in this field. Although the spaceborne InSAR technique is novel in its approach and appears to be a promising remote sensing method for dam monitoring, its measurements should always be validated or integrated with geodetic/GNSS data records. This is because it is still too early to trust observations from space as a unique data source for measuring surface displacements. Further projects details are outlined in Appendix A.4.

(2) Development of an IMS: Steps should be taken to develop an effective IMS for dams in order to ensure their safety and functionality. Tools such as advanced data acquisitions and computer software, as well as accurate data interpretation and highly trained personnel, are necessary for this development process. Further project details are outlined in Appendix A.4.

8.6.3 Workshop Feedback

According to the workshop participants, there is no question that monitoring in any form is fundamental to ensuring the safety of dams. While it was recognized that radar satellite-based monitoring can provide early indications of unexpected movement or behaviour, the need for monitoring internal changes in dams was also identified. This can be addressed by combining remote satellite monitoring with in situ sensing, as we proposed, which was highly regarded by the participants. It was argued by one participant that satellite monitoring of dams is not new as some InSAR contractors do this on a regular basis to fulfill a huge demand. It was clarified that data monitoring is one thing, but the physical interpretation of satellite measurements and their field validation against traditional surveying methods have not been done. It was also suggested to remotely monitor sedimentation, erosion and scour issues affecting many hydraulic structures. This can be addressed by conducting bathymetric and current-flow analyses from optical-band satellite imagery, which is a new research topic that can be explored in a follow-up NRC project. There were also questions related to image quality and frequency of acquisition for promptly monitoring damaged dams after a sudden event. A final suggestion was that a steering committee be formed to provide input and oversee the progress of the project. More details can be found in Appendix B.

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9 Geotechnical Challenges Due to Climate Change Effects

9.1 Introduction

The objective of this section is to identify geotechnical issues that may arise for dams as a result of the effects of climate change. As part of this task, currently applied geotechnical adaptation/mitigation strategies for the identified geotechnical issues are reviewed, potentially applicable technologies for the mitigation of these issues are sought, and recommendations for future research are offered. In particular, this section aims to identify knowledge gaps that need to be addressed and proposes future directions to overcome climate challenges such as increasing precipitation regimes and more frequent extreme events that can be expected due to climate change.

This section includes a review of the geotechnical challenges that dam owners and operators are already facing and identifies challenges that may arise or accelerate in the long term due to climate change predictions. Existing literature has been reviewed for potentially applicable technologies to respond to the gaps identified and recommendations for future research. Finally, this section outlines preliminary findings, proposed activities and future scope for the coming years.

As stated in the International Commission on Large Dams' (ICOLD) bulletin, Global Climate Change, Dams, Reservoirs and Related Water Resources:

- The climate change risk to dams, reservoirs and related water resources results from a combination of water hazards and water systems vulnerability, it is site specific and highly variable from one region to another one.
- Dams and reservoirs can also play a significant role in the adaptation to the climatic change: basins with significant reservoir capacity of regulation are more resilient to water resource changes, less vulnerable to climate change, and storage acts as a buffer against climate change.
- Hydropower, as one energetic use of dams and reservoirs, can also stand as a crucial tool in climate change mitigation. In general, together with a global warming and general average air temperature increase, it is predicted that higher latitudes will get more precipitation and lower latitudes will get less. Therefore, higher latitudes should prepare for more runoff and lower latitudes less (ICOLD, 2016).

In some cases, the challenge is not only facing a larger total precipitation or an average increase in annual temperature, but some locations will suffer more frequent extreme events and greater flooding together with more severe dry periods, although the evolution of extreme conditions is still characterized by high uncertainty. Table 9.1 lists the terms used in this section to indicate probability ranges referred to as calibrated uncertainty language in the Intergovernmental Panel on Climate Change's 5th assessment report (Mastrandrea et al., 2011). The terms very low, low, medium, high and very high are used to express assessed levels of confidence in findings based on the availability, quality and level of agreement of the evidence. Quantified likelihood assessments are made when confidence is high or very high and the available evidence is of a type that allows such quantification to occur.

Table 9.1 Probability in calibrated uncertain language

Term	**Probability (%)**
Virtually certain	99 to 100
Very likely	90 to 100
Likely	66 to 100
About as likely as not	33 to 66
Unlikely	0 to 33
Very unlikely	0 to 10
Exceptionally unlikely	0 to 1

The terms in Table 9.1 are used to express the assessed likelihoods of results or probability of some event or condition happening. The terms extremely likely (95% to 100% probability), more likely than not (> 50% to 100% probability), and extremely unlikely (0% to 5% probability) may also be used where appropriate.

9.2 Potential Impacts on New Dam Designs

Climate change is very likely to have a substantial impact not only on the ambient temperature, but also on the amount of precipitation that a geographic area is expected to receive. In some areas, the climatic changes will either increase or decrease the total precipitations. This will, in turn, have a significant impact on the design of future dams since historical data may no longer be reliable for use in the prediction of future water regime conditions. Generally, increased precipitation presents a greater concern to designers compared with decreased precipitation due to the increased pore water pressure generated below the dam foundation and along neighbouring slopes, as well as due to the increased erosion associated with increased flow.

9.2.1 Impacts of Increased Water Influx

From a design perspective, an increased peak water influx will require a larger reservoir capacity and, therefore, a taller dam leading to increased total stresses in the soil. In addition, the need to maintain the target operational water level and sufficient freeboard to accommodate increased peak influx will also require the spillway capacity to be increased to handle the larger flow of water. For this reason, a reliable hydrological model that is able to predict the changes in precipitation and expected runoff is the first tool required for the adequate design of future structures and for retrofitting existing structures. When considering the impacts of climate change on dam design, the main issues will be related to increased water levels and increased frequency of extreme events, which may increase the risk of overtopping. In addition, increased pore water pressure may lead to internal erosion and/or liquefaction and the requirement for increased protection from ice jams and associated outbursts of ice floes and melting ice. Other challenging scenarios may arise in areas where several dams are located along the same river; an increased outflow from the first dam upstream could contribute to the early thaw of ice and frozen areas downstream, which could lead to replicating and possibly augmenting unwanted ice floes and melting ice situations in subsequent dams.

9.2.1.1 Challenges due to Increased Water Influx

Given the uncertainty surrounding the modeling of future events and the large uncertainties surrounding climate change, designers will have to consider the possibility that even the most pessimistic predictions of outflows may underestimate the conditions that a new structure may encounter. To account for this uncertainty, it may be necessary to design larger portions of dams to handle overflow. If larger portions of new or existing dams—or, in some cases, the complete structure—need to be treated as overflow structures, then optimization of erosion-resistant designs for the downstream faces of the dams, such as the ones proposed by Helper et al. (2012), must be considered. New methods to analyze the effect of flow on sloped dams may prove to be very useful in these circumstances, e.g., to determine the interstitial velocity of flow within a riprap or gabion cover (Keene, 2019), in order to assess the risk of erosion of the underlying material. Vegetative covers can be used as affordable means of offering some measure of protection to the downstream faces of dams. The flow regimes that can be considered based on the types of vegetation used and how the vegetation's own response to the climatic change could affect the expected results would be of great importance and would offer important avenues of research.

Another important design consideration regarding new dam structures is the design criteria for erosion protection downstream of the dam. The zones affected by critical erosion due to outflow from the dam may be increased by two main factors: the increased outflow from the dam, not only during peak flow but also during normal operations; and the increased sensitivity of the downstream slopes to toe erosion due to the general increase in the groundwater table expected from increased precipitation.

New considerations will need to be made for conditions upstream of the dam, where natural slopes that were considered to be stable have the potential to become unstable under future precipitation regimes if the groundwater table is raised (Segoni et al., 2013). Standard practice would be to quantify the stability of such slopes using current conditions or predicted conditions based on historical data. However, an increase in the precipitation regime that would significantly increase the piezometric level could mean that slopes that were deemed to have a sufficient factor of safety could see this factor of safety significantly reduced in the future. This increased risk of instability will happen all along the stream channel upstream of the dam, and increased erosion (due to higher flows in those streams) will further increase the risks of slope failure upstream. The risks associated with failures upstream of the reservoir are mainly an operational concern. The main impact of the influx of additional sediment will be on the performance and maintenance of the mechanical/electrical systems associated with the dam. These possible events need to be considered in the design phase if such an influx of sediment can adversely impact the operation of the dam in its primary function.

From a safety point of view, it is important to consider the effects of slope failures on tributary rivers as well as around the dam perimeter. Failure of slopes may result in hydrodynamic forces generated by the rapid fall of soil mass into the reservoir, which may damage the dam structure, or result in localized overtopping. Because of the extensive nature of the slopes for which such an assessment needs to be made, it may not be practical, for design purposes, to fully model the site and apply future predictions of the climate model to assess the future susceptibility to slope failure. For coverage of wide areas, it is often preferable to use remote sensing technologies to collect data for the entire area of interest, which can then be processed and analyzed to make the required assessments.

9.2.1.2 Currently Applied Methods to Address Challenges Due to Increased Water Influx

Remote sensing tools such as LANDSAT photography, drone photographs or Interferometric Synthetic Aperture Radar (InSAR) technology have been utilized to assess ground displacement patterns and post-earthquake landslide susceptibility (Omar et al., 2007; Chen et al., 2020). Such methods, while powerful, can only examine the potential of slope failures based on existing conditions in the field. However, there is still a need to establish susceptibility based on predicted changes in field conditions. These methods should be used in conjunction with other methods that are designed to investigate changes in susceptibility based on climate change predictions.

Some methods based on artificial neural networks (ANNs) have been used to predict variations in groundwater levels under various climatic conditions, based on a knowledge of the subsoil conditions (Coppola et al., 2003; Tsanis et al., 2008). There is also some work on methods to predict variations in the groundwater table at a specific location (Javadinejad, 2021). Fundamentally, ANNs are interpolation algorithms that are not well suited to extrapolate trends beyond the limits of the existing conditions used for the training data. Upon examination of the literature, using these methods to predict the susceptibility of slopes to failure based on models of future precipitation is likely an area that needs further development. The new models to be developed should consider the variability of soil parameters and should also incorporate detailed modeling of seepage and slope stability to simulate changing conditions under predicted climate change conditions. This type of detailed physics-based model can be used to train ANN models to evaluate the susceptibility of current slopes to future changes in climate.

An additional area of research to consider for new dam designs is the development of effective and economical means of slope protection via water ingress prevention or reinforcement that would be applicable to prevent the failure of dams. A particular area of interest in this regard is the use of capillary barrier systems to offer additional protection against water infiltration, thus increasing the stability of existing slopes (Rahardjo et al., 2016; Li et al., 2021). Capillary barrier systems can be engineered using a variety of natural and synthetic materials (Krisdani et al., 2010; Rahardjo et al., 2013), and take advantage of vegetation (Li et al., 2021). Although a growing body of knowledge has increased in this area, there is a need to study the types of weather patterns that would see such capillary barrier systems become ineffective and examine whether breakthrough events can be healed using techniques as suggested by Salah (2020).

9.2.2 Impacts of Decreased Water Influx

In general, most negative impacts caused by a general reduction of the water influx to the dam reservoir will affect the operation of the dam and may result in insufficient flow to serve its main design goals. If the minimum water level of the reservoir decreases, this could potentially result in significant reductions in the pore water pressure experienced by the soil and rock strata situated below the dam. This reduction in pore water pressure can have some positive impacts as it will result in an increase in the effective stress below the dam and within the surrounding slopes, thus improving the shear strength of the soil and reducing the risk of slope failures under static loadings.

Some considerations will have to be taken into account when analyzing the conditions of the strata below the dam. Climate change effects will likely be observed well after the completion of the construction of new dams; the conditions below the dam should be expected to experience higher pore pressures initially, which would later be reduced. Because of this, late-stage reduction in pore water pressure will result in an increase in the effective stress that, in turn, will cause additional settlement. This emphasizes the need to ensure that compressible soil layers are removed or adequately treated to take these future effects of climate change into account. Even if the dam rests on rock, the potential deformation of the rock under the increased effective stresses should be considered, and steps should be taken to monitor the deformation of the dam structures. A discussion on using remote sensing for the monitoring of site conditions after construction will be left for the next section of the report.

An additional concern arising from a future decrease in pore pressure and an increase in effective stress would have to be considered in the presence of a non-cohesive foundation below the dam or below neighbouring slopes. Although an increase in effective stress is generally a desirable feature when considering the shear strength of soil, this condition may increase the potential for liquefaction in the event of seismic activity. This increase in effective stress could potentially make the soil more susceptible to liquefaction. Induced liquefaction can occur within “loose” cohesionless soils because when such materials are sheared, they tend to reduce in volume. In the case of seismic loading, the rapid directional change of the loads means that the soil is sheared in an undrained condition, and the tendency of the soil to decrease in volume translates into an increase in pore water pressure instead.

In contrast, when “dense” cohesionless soils are sheared, they exhibit dilatancy. Under undrained conditions, soils cannot increase volume and as a result, pore water pressure is reduced, which increases the effective stress and shear strength of the granular soil and decreases the risk of liquefaction. It is important to note that the term “loose” used in this context is a very relative term that depends on the confining pressure of the soil element. Effectively, the deeper a soil element is, or the larger the confining pressure, the greater the density of the soil must be for it to be considered as “dense”. This is because the relationship between the void ratio and the normal effective stress at steady state (i.e., the state where, under continued shear, no further changes in volume will occur) is defined by the critical state line (CSL) as shown in Figure 9.1.

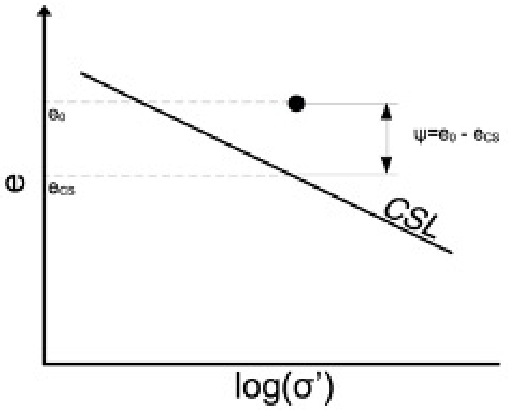


Figure 9.1 State parameter (*ψ*) and critical state line (CSL), plotting void ratio (e) against the log of the effective normal stress (σ'); figure adapted from Sottile et al. (2019)

In Figure 9.1, when soil is sheared at given normal stress, the volume of the soil will tend to change until the CSL is reached, after which no further volume change will occur under additional shearing. Practically, this means that any soil element that plots below the CSL will tend to expand under shear until the CSL is reached. Such a soil element is not susceptible to liquefaction under seismic loading.

Alternatively, if a soil element is found above the CSL, seismically induced shear would induce the soil to contract, thus increasing pore pressures locally and increasing the potential for liquefaction. A state parameter *ψ* (Been and Jefferies, 1985), defined as the difference between the in situ void ratio (e_0) and the critical state void ratio at the same confining stress (e_{cs}), can be used to determine how far one is from the CSL and whether a seismic load is likely to induce liquefaction. Soil at a given void ratio may behave as a dense soil under lower effective stress and as a loose soil under a larger normal effective stress, which can lead to unintuitive behaviour of the soil. Let us consider, for instance, the hypothetical scenario illustrated in Figure 9.2.

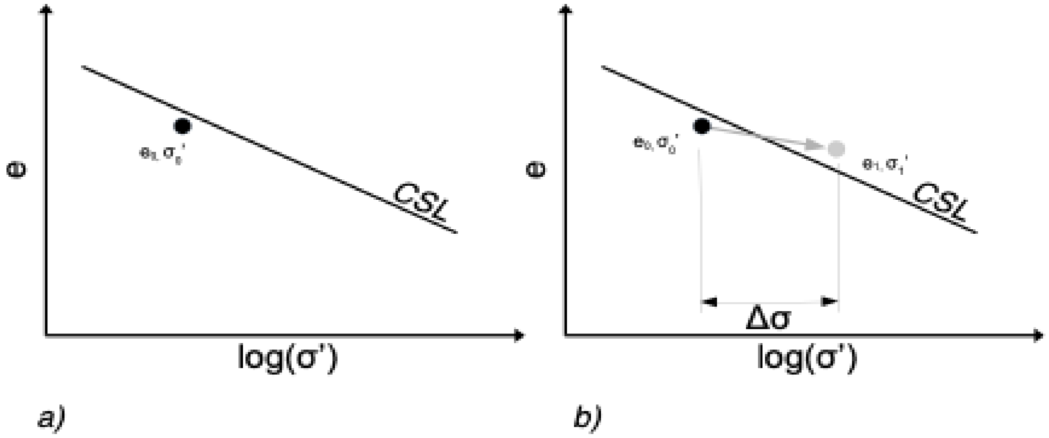


Figure 9.2 Evolution of void ratio (e) and the log of effective normal stress (σ') for a hypothetical soil specimen (Infante and Hiedra Cobo, 2022)

A soil specimen initially lying below the CSL (as shown in Figure 9.2a) would behave as dense sand, which means that under seismic shear loading it would display dilatant behaviour. As such, negative pore pressures would be generated under seismic loading, and the soil mass would not be susceptible to seismic liquefaction. However, if the groundwater table was to be lowered due to more intense droughts caused by climate change, then the effective stress would increase. Figure 9.2b shows such an increase of normal stress, denoted by $\Delta\sigma$. In this hypothetical scenario, the increase in effective stress results in a decrease in the void ratio, from e_0 to e_1 (i.e., the soil experiences compression under the added stress). However, this change in the void ratio over the change in normal stress is smaller than the slope of the CSL.

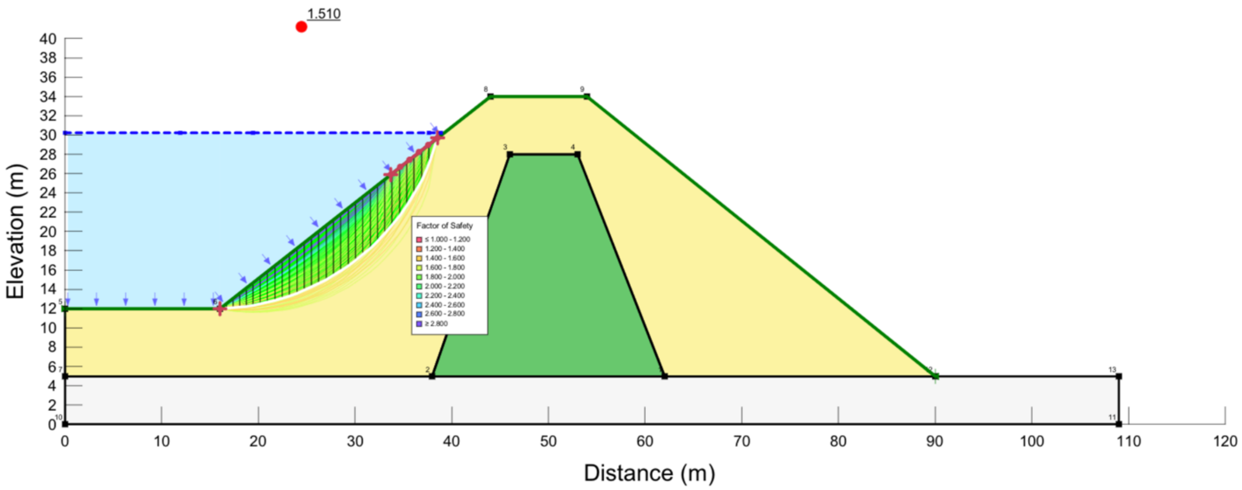
This causes the void ratio, which initially was e_0 (below the CSL, indicating that the soil is not susceptible to liquefaction), to move across the CSL towards e_1, which indicates that the soil is susceptible to liquefaction under seismic loading. In such a scenario, an increase in the effective stress caused by a reduction of the groundwater table and, therefore, the pore pressure, would result in an increased susceptibility to seismic liquefaction. This is a counter-intuitive behaviour as liquefaction is associated with high pore water pressures, and an increased normal effective stress is normally associated with greater shear strength and improved stability. It is this unexpected behaviour that makes this scenario particularly important to identify in the field.

In practice, the CSL line may be established by conducting a number of laboratory tests, such as triaxial tests, direct shear tests or modified ring shear tests. However, it should be noted that triaxial tests are not the best types of laboratory tests to be used in this context since the maximum deformation is limited. Direct shear tests can be used, although the effective shear deformation imposed increases through the use of shear direction reversal. The best laboratory tool to use for this type of test is probably the modified ring shear test, as it effectively provides unlimited shear deformations. Unfortunately, the modified ring shear test device is not currently a standard piece of equipment in geotechnical laboratories. Although the use of the CSL line method to determine the state of a soil element is a relatively well-established technique, it is essentially a design tool that enables an engineer to establish the stress and density parameters that will ensure safe conditions for the dam.

An additional advantage of using the CSL as an assessment tool is that it can be obtained from disturbed specimens. This characteristic is even more important given the difficulty associated with obtaining undisturbed specimens of cohesionless soils. In practice, the problem is determining where the current site conditions place the in situ soil with respect to the CSL, particularly given the difficulties in obtaining undisturbed specimens of granular soils. It is possible, however, to use field tests such as the standard penetration test (SPT) or the cone penetration test (CPT) to establish correlations. The piezocone test (CPTu), in particular, can prove very effective in determining if a soil layer is susceptible to liquefaction in its current condition, because it measures the pore water pressure as the cone is inserted into the soil. Such work has already been presented by various researchers (Ahmadi et al., 2009; Du et al., 2019). However useful this knowledge is, it can only let the practitioner know if soil in its present condition is likely to experience seismic liquefaction; it cannot be used to predict under which type of groundwater conditions the risk of liquefaction may manifest itself or cease to be a concern.

Rapid drawdown is another scenario that is important to evaluate. Rapid drawdown is typically related to the high demand for water from communities and agricultural users due to elevated ambient temperatures, causing a sudden decrease in the water level of a dam. If it is necessary to drain the reservoir quickly, the pore-water pressures within the embankment may remain relatively high while the stabilizing effect along the upstream side of the embankment is removed. This process is typically referred to as "rapid drawdown" and can cause instability of the upstream face of the embankment.

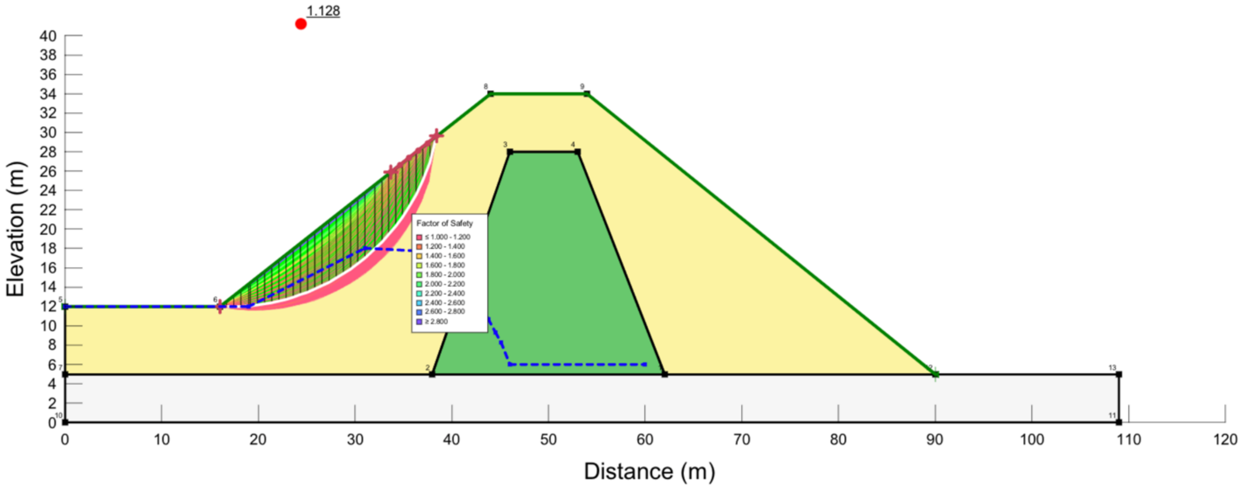
To illustrate the effect of rapid drawdown, a generic case study has been evaluated as part of this gap analysis using the GeoStudio suite of software from GeoSlope to simulate the response of a generic structure for the two scenarios of interest. The results demonstrated a decrease in the factor of safety (FS) for the upstream slope from $FS_{\text{before drawdown}} = 1.510$ down to $FS_{\text{after drawdown}} = 1.128$ (see Figure 9.3 for normal operating conditions before drawdown and Figure 9.4 for conditions after drawdown).



Materials
🟩 Clay Core
🟨 Embankment Material

Color	Name	Slope Stability Material Model	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)
🟩	Clay Core	Mohr-Coulomb	18	15	15
🟨	Embankment Material	Mohr-Coulomb	18	8	30

Figure 9.3 Stability analysis before drawdown



Materials
🟩 Clay Core
🟨 Embankment Material

Color	Name	Slope Stability Material Model	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)
🟩	Clay Core	Mohr-Coulomb	18	15	15
🟨	Embankment Material	Mohr-Coulomb	18	8	30

Figure 9.4 Stability analysis after drawdown; note the decreased FS from 1.510 to 1.128

9.3 Gap Analysis, Future Directions and Workshop Feedback

9.3.1 Identified Gaps

9.3.1.1 Existing Dams

A particular concern for long-term dam stability of existing dams is the possible presence of loose sand in the body of the dam. This condition may be found in older structures where the soil was not appropriately compacted (e.g., hydraulic fill structures). The danger presented by loose sand in the structure of an earthfill dam is that it may experience static liquefaction under a regime of increased pore water pressure. This pore water pressure increase may be caused by peak water levels that are higher than allowed in the design or simply high enough water levels sustained for longer periods than considered at the design stage.

In such cases, the pore water pressure increases may be enough to cause liquefaction of the sand layer or enough to only cause a reduction in its shear strength, thereby causing a slope failure that can damage the dam. A stark reminder of this risk has been provided by the failure of the Edenville dam, as indicated by the Independent Forensic Team Interim Report (IFT, 2021). The findings of this report established that the root cause of the failure was most likely the static liquefaction of sand in the Edenville Dam, which caused a breach in the structure. The subsequent flow caused failure through overtopping and erosion of the downstream face of the Sanford dam located downstream of the Edenville dam. In this case, research evaluating existing soils that present a risk of liquefaction using geophysical investigation would be of most interest, while general approaches to retrofit such dams would also be a useful area of research.

Another concern is the increased risk of overflow for existing dams that were not designed for overtopping. Since the capacity of dams is based on historical rainfall data, in scenarios where climate change is expected to increase regional precipitations, it is likely that overtopping events will become more frequent (medium confidence). As such, it is very important to ensure that such structures are retrofitted in a manner that allows them to withstand overtopping events in scenarios where enlarging the spillway to a sufficient degree is not feasible. The various methods available to improve the erosion resistance of a dam should therefore be considered (e.g., using rip-rap or vegetative cover). The intensity and frequency of extreme precipitation events is likely to increase with global warming (Myher et al., 2019). Under future climate scenarios, the risk of failures around the dam is likely to increase. The increase in the frequency of extreme precipitation (i.e., the number of events per unit time with intensity above a given threshold) has generally received much less attention. Under changing climate conditions, it is not appropriate to use intensity-duration-frequency (IDF) curves based on historical data alone for long-term planning. To account for the effect of climate change on extreme rainfall, ECCC et al. (2022) and other authors (Schardong et al., 2018; Martel et al., 2021) recommend the use of a scaling methodology to adjust IDF curves.

Based on the literature reviewed here, the main knowledge gaps identified in this section, which are likely to affect existing dams and will need to be addressed by further research, are:

(1) The use of in situ tests such as the CPTu and the pore water pressure response measured to evaluate the state parameter of the sand, combined with laboratory tests to establish the CSL of the same soil. These tests would be useful in predicting the changes in susceptibility to seismic liquefaction of granular soils masses.
(2) The use of existing software to simulate various scenarios throughout the life of a dam in order to identify critical conditions that need to be addressed before construction; and for the case of existing structures, as part of a retrofit or rehabilitation program.
(3) The development of new advanced methods based on ANNs to predict variations in groundwater levels under various climatic conditions to assess the susceptibility of current slopes to future changes in climate.

9.3.1.2 New and Existing Dams

The main criteria used to prioritize the research needs related to the impact of climate change on dam design and management deal with minimizing the risks to human life and welfare. In this sense, priority should be given to knowledge gaps that affect the durability, stability, operation and maintenance of existing dams since, at the time of their construction, they were not designed to take into account the effects of climate change. The main gaps identified for new and existing dams are as follows:

(1) Assessment of the presence of liquefiable sand (dynamic or static liquefaction) in existing embankment structures.
(2) Develop retrofitting procedures to prevent liquefaction of existing liquefiable layers.
(3) Assessment of the viability of vegetative covers as protection for overtopped dams.

(4) Assessment of the instability of slopes surrounding the dam under future rainfall patterns, using a combination of remote sensing techniques and ANNs that have been trained using simulations of seepage and slope stability that make use of future climate predictions.
(5) Implementation of an early warning system based on the CSL to provide risk evaluation to dam operators and communities that are potentially at risk from slope failures.
(6) Assessment of interstitial flow velocity in rip-rap and gabion-covered dam faces and how it may affect the erosion of subjacent layers and the channel bed at the bottom of the dam.
(7) Research into the correlation between in situ tests and the state parameter of cohesionless soils susceptible to liquefaction so that the CSL may be used to predict future behaviour.
(8) Use of remote sensing for the monitoring of dam settlement potentially caused by an increase in effective stress.

Given that various known techniques could be used to mitigate the risk of a slope failure due to changing conditions, the following two areas of research do not have the same priority as the previous eight, although they may decrease the risk of a slope failure.

(9) Evaluation of capillary barrier systems and other means of protecting slopes around dams against instability, which could cause damage.
(10) Evaluation of innovative erosion protection schemes downstream of the dam in an effort to improve current practices.

9.3.2 Future Directions

9.3.2.1 Existing Dams Pertaining to Geotechnical Stability

Designers of future dams will likely be concerned with extreme scenarios that may alternate between increased water influx into the dam reservoir and load cases related to a decrease in water inflow.

The main areas of research pertaining to scenarios involving increased precipitations are:

(1) Assessment of the viability of vegetative covers as protection for overtopped dams.
(2) Assessment of interstitial flow velocity in rip-rap and gabion-covered dam faces and how it may affect the erosion of subjacent layers and the channel bed at the bottom of the dam.
(3) Evaluation of innovative erosion protection schemes downstream of the dam in an effort to improve current practices.
(4) Assessment of the instability of slopes surrounding the dam under future rainfall patterns, using a combination of remote sensing techniques and ANNs that have been trained using simulations of seepage and slope stability and that make use of future climate predictions.
(5) Evaluation of capillary barrier systems and other means of protecting slopes around dams against instability, which could cause damage.

The research areas pertaining to scenarios involving reduced precipitation are:

(1) Use of remote sensing for the monitoring of dam settlement potentially caused by an increase in effective stress.
(2) Research into the correlation between in situ tests and the state parameter of cohesionless soils susceptible to liquefaction so that the CSL may be used to predict future behaviour.
(3) Integration of remote sensing techniques to estimate the susceptibility of a slope to failure with ANNs that are trained with actual numerical simulations of the effect of changed rainfall conditions on the pore pressure conditions and slope stability.

9.3.2.2 New and Existing Dams Pertaining to Operating Environments

Owners and operators of new and existing dams will have to consider changes to their operating environments that will add new challenges and greater risks of overtopping or encountering other conditions of failure. Various areas of research of interest for the operation of existing dams are shared with the research needed for the design of future dams.

The areas of research of interest in scenarios involving increased precipitations are:

(1) Assessment of the presence of liquefiable sand (dynamic or static liquefaction) in new and existing embankment structures.
(2) Develop retrofitting procedures to prevent liquefaction of existing liquefiable layers.
(3) Assessment of the viability of vegetative covers as overtopping protection for new and existing dams.
(4) Assessment of interstitial flow velocity in rip-rap and gabion-covered dam faces and how it may affect the erosion of subjacent layers and the channel bed at the bottom of the dam.
(5) Evaluation of erosion protection schemes downstream of the dam as compared to current practice.
(6) Assessment of the instability of slopes surrounding the dam under future rainfall patterns, using a combination of remote sensing techniques and ANNs that have been trained using simulations of seepage and slope stability that make use of future climate predictions.
(7) Assessment of the risk of slope failure and the development of early warning systems based on historical data of rainfall and recorded slope failures.
(8) Development and validation of an early warning system for slope stability similar to the method implemented in Japan and elsewhere, but with validation based on data from Canadian dams.
(9) Evaluation of capillary barrier systems and other means of protecting slopes around dams against instability, which could cause damage.

The research areas of interest for scenarios involving reduced precipitation are:

(1) Use of remote sensing (InSAR analysis) for the monitoring of dam settlement potentially caused by an increase in effective stress.

(2) Research into the correlation between in situ tests and the state parameter of cohesionless soils susceptible to liquefaction so that the CSL may be used to predict future behaviour.

Proposed project details are outlined in Appendix A.5.

9.3.3 Workshop Feedback

The workshop participants noted the importance of focusing on the stability and integrity of aging dams as it was pointed out that many of Canada's major dams are quite old and were constructed before modern dam construction practices began. Some participants also indicated that owners are spending substantial amounts of money on aging dams, which may be susceptible to climate change risks. As such, studying the geotechnical challenges due to climate change with a focus on aging dams is critical. Additionally, participants noted that since old dams were not always built with the same degree of knowledge or rigorous engineering practices compared with newer dams, their failure modes might differ. It was noted that failure modes will be directly affected by the changing climate, water levels, temperature changes, etc. Some participants also pointed out that, compared with concrete dams, earthfill dams and rockfill dams tend to be far more complex. As such, there are a number of elements in the behaviour and integrity of earthfill and rockfill dams, such as creep behaviour, surface erosion and internal zoning, that need to be studied. More details can be found in Appendix B.

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10 Climate Change Impacts on Concrete Dams

10.1 Introduction

Many aspects of climate change are expected to negatively impact the structural stability of concrete dams and cause the degradation of concrete materials. Horizontal loads applied on dams are expected to increase (e.g., hydrostatic loads increase as a result of extreme winter stream flows and sediment loads increase due to increased upstream erosion) (Bowles et al., 2013; USBR, 2014; Fluixá-Sanmartín et al., 2018). These same trends are expected to lead to more frequent and severe instances of spillway and stilling basin erosion and this may warrant increasing the size of reservoirs. Climate change is also expected to lead to accelerated deterioration in dam bodies and spillways, while higher temperatures are expected to increase the rate of alkali-aggregate reactions. Summer drought followed by winter precipitation is expected to increase sulphate concentrations in basins, increasing the likelihood of sulphate attack. Finally, higher temperatures are expected to increase temperature differentials in concrete dam bodies, increasing thermal cracking concerns (Moyo and Nyoni, 2020). These impacts may lead to dam failures due to uncontrolled releases caused by overtopping and seepage through dams. Existing dams may need to be repaired or upgraded to address these concerns (Choi et al., 2018).

The main objectives of this section are to highlight the impact of climate change on the structural stability of existing concrete dams, the degradation of concrete materials, and the performance of steel gates and penstocks. This section also outlines the available restoration approaches for concrete dams, which could efficiently be employed as future adaptation methods to climate change. Furthermore, this section describes existing risk assessment tools for dams that incorporate the impact of climate change in the scoring, while gaps in knowledge and the future research required are presented at the end of the section.

10.2 Impacts of Climate Change on Structural Stability and Concrete Degradation

10.2.1 Structural Stability

One of the most significant impacts of climate change on the structural stability of concrete dams is that horizontal loads, including hydrostatic loads and sediment loads, applied on existing dams will increase (Fluixá-Sanmartín et al., 2018). The causes of this increased load include increased precipitation and stream flows. The increase in load may be such that the total horizontal load exceeds the design load of the existing dam, causing the potential for failure if preventative measures are not taken.

Since 1948, Canada's average annual precipitation has risen by 20%, and this trend is expected to continue and intensify (Bush and Lemmen, 2019). Furthermore, snowmelts are expected to shift closer to the winter season than to spring, which will increase winter stream flows. Finally, extreme precipitation events are expected to increase in frequency, which will increase stream flows periodically (Warren and Lulham, 2021). Ehsani et al. (2017) performed a study modeling the effects of climate change on reservoir operations in the northeastern USA and showed that increased precipitation in winter followed by earlier snowmelt periods would increase the total available water resources by 22% in the December to March period between 2017 and 2099. The results implied that existing dams and reservoirs were under designed for such an increase (Ehsani et al., 2017). Since similar conditions are expected in Canada, and considering the age of existing dams, the conclusion is that Canadian dams are under designed for future increases in precipitation and winter stream flows. The inability of current dams to handle the projected increase in late winter and early spring stream flows is of particular concern, as snowmelt runoff floods are already the most common type of flooding in Canada (Environment and Climate Change Canada (ECCC), 2013). The failure of the Spencer Dam on the Niobrara River near Spencer, Nebraska, USA, in March 2019 is a prime example of the consequences that can arise when dams are under designed for the combination of extreme precipitation events and snowmelts. The Spencer Dam failure occurred after a series of extreme and unusual weather events.

Another concern associated with higher winter stream flows is a higher potential for sedimentation. Sedimentation occurs when sediment produced from runoff erosion is transported by the upstream river and deposited into the dam reservoir (United States Department of the Interior, 1987). While some sedimentation will always occur regardless of the effects of climate change, the projected increased frequency and intensity of precipitation and extreme weather events may increase erosion rates and sediment loads in runoff entering rivers. Furthermore, the same components of climate change can increase the velocity of rivers, increasing erosion in the riverbed itself (United States Environmental Protection Agency, 2020). Sedimentation has many negative impacts on the operation and lifespan of dams. The main and most relevant impact is that the sediment occupies some of the reservoir volume, reducing the water-carrying capacity of the reservoir. Significant accumulations of sediment in the dam reservoir can also impose an additional horizontal load on the dam. A reduction in the lifespan of dams has been observed worldwide, as there is an existing increasing trend in the sediment runoff in rivers. For example, the Tarbela Dam in Pakistan has lost about 1.5% of its reservoir volume every year since it opened in 1976 due to sedimentation (Novak et al., 2004). It is estimated that losses in the total reservoir capacity of dams worldwide due to sedimentation are approximately 0.5% to 1.0% per year (White, 2001). Designers must make provisions for sediment storage based on estimated sedimentation (United States Department of the Interior, 1987). However, as many existing dams were designed long before climate change was a concern, they may have been under designed for the possible increased sedimentation due to climate change. As such, the height of these dams may need to be increased.

In addition to higher winter and spring flows and sedimentation causing increased reservoir levels and horizontal loads on dams, some other factors will create a need for larger reservoirs and, as a result, dams that can resist higher horizontal loads. Seventy percent of the large dams in Canada are used for hydroelectric generation (CDA, 2019). In the summer months, rising temperatures will lead to an increase in evaporative water losses (Bush and Lemmen, 2019), while a longer growing season and hotter days will increase the demand for water and energy (ECCC, 2019). Therefore, an increase in energy demand has an implication for dams as well. The power that is generated by a dam is proportional to the difference between the upstream and downstream water level, also known as the gross head (Novak et al., 2004). Therefore, to compensate for the additional demand for energy, the reservoir levels in certain dams may need to be increased by increasing the dam height and load-bearing capacity of the dam.

10.2.2 Spillway and Stilling Basin Erosion

Another impact of climate change on dams is that spillways will be increasingly prone to erosion. The trends contributing to rising reservoir levels, particularly during the winter snowmelt period, will also contribute to the increasing potential for spillway erosion. These trends include rising annual precipitation, earlier snowmelts, and the increased frequency and intensity of extreme precipitation events (Bush and Lemmen, 2019). If dam owners and operators maintain reservoir volumes at the current levels, these additional flows will need to be released through the existing spillways and stilling basins.

Hydrological aspects are one of the main influencing factors on spillway design, including the estimation of the inflow design flood, the selection of the spillway design flood, the determination of the spillway design flow, and the determination of the frequency of spillway use (Khatsuria, 2005). The design flood is typically the 1 in 10,000-year flood, also known as the probable maximum flood (Chadwick et al., 2013). The median year of construction completion of large dams in Canada is 1969 (CDA, 2019). Since then, not only has the methodology of estimating the design flood changed, but the trends in hydrology have also changed (Clavet-Gaumont et al., 2017). Clavet-Gaumont et al. (2017) performed a study estimating the changes in the probable maximum flood due to climate change in five Canadian river basins. The study used regional climate model simulations to calculate the median projected change in the probable spring flood between 1970 to 2000 and 2041 to 2070. The results of the simulations showed that, due to climate change, the future probable maximum flood in spring would have median increases of -1.5% to 20% in the five basins (Clavet-Gaumont et al., 2017). The projected changes in the probable maximum flood vary significantly based on the watershed and climate scenario. However, climate change will likely increase probable maximum flood values (Ouranos, 2015). Considering that the median year of construction completion of large dams in Canada is 1969 (CDA, 2019), it is likely that many spillways and energy dissipators are under designed for the projected increase in probable maximum floods, particularly in older dams.

The projected increase in probable maximum floods will increase the flow rates and velocities of spillway discharges if operators maintain current reservoir levels. The main issue associated with high flow rates and velocities is erosion and cavitation damage (Novak et al., 2004). Erosion damage occurs when the spillway's concrete surface is physically worn by the water and water-borne sediments (Dolen et al., 2003). Cavitation occurs when the local pressure in flowing water is reduced to the vapour pressure, which causes bubbles (i.e., cavities) to form. As the bubbles grow and travel to an area where the pressure is higher, they eventually collapse. When the collapse occurs adjacent to a solid object, such as the surface of a spillway, very high pressure is generated on the surface. When these impacts occur multiple times, erosion of the concrete can occur, which is known as cavitation pitting (Khatsuria, 2005).

Higher flow rates in the upstream river caused by increased precipitation and extreme weather events can increase the amount of sediment that is transported to the dam (United States Environmental Protection Agency, 2020). Furthermore, the higher flow rates can increase the intensity of cavitation. This combination of factors increases the likelihood and magnitude of spillway surface erosion. A survey performed by the International Commission on Large Dams in 1980 found that most of the spillways with surface erosion were operating with maximum flow velocities over 30 m/s, with most of the damage being caused by cavitation (Novak et al., 2004). As probable maximum floods are projected to increase and are likely higher than the design floods for many dam spillways in Canada, it is possible that spillway velocities may increase to this threshold without any retrofitting or mitigation measures.

A recent example of the impacts of spillway erosion is the failure of the Oroville Dam spillway near Oroville, California, USA, in 2017. The Oroville Dam is the tallest dam in the USA and was completed in 1968. It is an earthfill embankment dam; however, the service spillway consists of a concrete chute (France et al., 2018). On February 2, 2017, a rainstorm in the river basin began, and on February 6, 2017, the spillway gates were opened to lower the reservoir level and prepare for further precipitation. However, on February 7, operators noticed discoloration in the discharge, and discharge was halted, revealing a large hole on the spillway surface. Due to the rising water levels in the reservoir, there was not enough time to repair the service spillway, so the service spillway was closed and flows began to pass over the emergency overflow spillway (Koskinas et al., 2019). The hillside where the emergency spillway was located began to experience rapid erosion and head cutting, posing a risk of failure to the emergency spillway weir. To avoid this, the service spillway was reopened, and the erosion on the spillway surface worsened. The resulting damage required USD 1.1 billion in repairs and recovery, and the incident is considered one of the most serious dam safety incidents in American history (France et al., 2018).

As the median year of construction completion of large dams in Canada is 1969 (CDA, 2019), probable maximum floods in the future are likely to exceed the design floods for many spillways in Canada. This will increase the discharge flow rates and velocities in spillways and may also increase the amount of sediments in spillway discharge flows (United States Environmental Protection Agency, 2020). These are factors that increase the likelihood and severity of spillway erosion and cavitation (Novak et al., 2004), therefore, spillway erosion is an important area of concern for dam safety going forward.

10.2.3 Concrete Deterioration

An additional concern for concrete dams arising from climate change is the accelerated deterioration of concrete in dam bodies and spillways caused by thermal cracking, alkali-aggregate reactions, freeze-thaw cycles and sulphate attacks (Moyo and Nyoni, 2020).

Climate change is expected to contribute to cracking of dams in the future (Bush and Lemmen, 2019). Average temperatures have risen and are projected to continue to rise. Extreme temperatures are expected to become higher and more frequent (Bush and Lemmen, 2019). The rising temperature trend will affect the likelihood and magnitude of thermal cracking, freeze-thaw cycles, and alkali-aggregate reaction-induced cracking. Furthermore, future droughts and increasing winter precipitation are expected to increase the likelihood and intensity of sulphate attacks (Warren and Lulham, 2021). The likelihood of thermal cracking, alkali-aggregate reactions, freeze-thaw cycles and sulphate attacks will increase due to the effects of climate change and this creates a heightened cause for concern of concrete deterioration in dams (Hanson, 2016).

10.2.3.1 Thermal Cracking

Thermal cracking occurs when there is a large temperature differential within mass concrete. The cooler portion of the concrete experiences a larger contraction than the warmer portion, and the cool portion becomes restrained by the warm portion. This generates tensile stresses, and once these stresses exceed the concrete's tensile strength, cracking occurs (NRMCA, 2009). Thermal cracking is an issue that can occur in both the short term and long term. In the short term, immediately after concrete casting, plastic shrinkage cracking is a possibility, especially in hot and dry ambient conditions. Plastic shrinkage cracks appear when the water near the surface evaporates faster than it can be replaced by bleeding water. This causes shrinkage, creating tensile stresses and the appearance of cracks (Hanson, 2016). In the long term, high temperatures can cause the cured concrete to expand. If the concrete is restrained, tensile stresses will be generated and cracks will appear. This phenomenon is known as temperature cracking (NRMCA, 2009). Since the possibility and extent of thermal cracking are directly related to hot ambient temperatures, projected global warming makes thermal cracking a growing concern in concrete dams (Moyo and Nyoni, 2020).

10.2.3.2 Alkali-Aggregate Reactions

Another concern caused by rising temperatures is their ability to accelerate alkali-aggregate reactions. There are two types of alkali-aggregate reactions depending on the type of aggregate used in concrete: alkali-silica reactions and alkali-carbonate reactions. Only alkali-silica reactions will be discussed, as the aggregate required for alkali-carbonate reactions is rarely used in concrete construction (Portland Cement Association, 2019a). In general, alkali-aggregate reactions take place when hydroxyl ions in the cement react with the aggregates. In the case of alkali-silica reactions, aggregates containing silica react with the alkali hydroxide in the concrete, forming a gel. The gel swells as it absorbs water from the surrounding concrete (Ratnam and Mahure, 2008). As the gel continues to expand, stress is imposed on the concrete, leading to cracking and spalling (Portland Cement Association, 2019a). Alkali-aggregate reactions, like all other chemical reactions, are influenced by temperature. As the ambient temperature increases, the rate of the production of the gel also increases. However, at the same time, higher temperatures lower the viscosity of the gel, allowing it to pass more easily through the cracks and pores of the concrete. This slightly offsets the negative effects of the increased rate of reaction (Ratnam and Mahure, 2008). Therefore, based on the relationship between the ambient temperature and the rate of reaction, the projected rise in future temperatures is likely to increase the impact of alkali-aggregate reactions on dams.

10.2.3.3 Freeze-Thaw Cycles

An additional impact of rising temperatures leading to the deterioration of concrete in dams is more frequent freeze-thaw cycles. This trend is already being observed in Canada, with Southern Ontario having the highest rate of increase in the number of freeze-thaw cycles (Canadian Council of Ministers of the Environment, 2003). In the future, higher temperatures are expected to lead to a continued increase in the number of freeze-thaw cycles in the regions of Canada with the coldest winter climates. However, in regions with milder winter climates, further warming is expected to lead to an eventual decline in the number of freeze-thaw cycles (Auld et al., 2007). These trends in the number of freeze-thaw cycles can be explained through trends in temperatures. As aforementioned, winter temperatures and annual lowest daily minimum temperatures are expected to increase (Bush and Lemmen, 2019). In the coldest winter climates, this would cause more days with fluctuations around the freezing point, explaining the expected rising trend in freeze-thaw cycles. However, in milder climates, the temperature trends would lead to fewer days with temperatures below the freezing point, which would explain the eventual decrease in freeze-thaw cycles. Notably, in the short to medium term, freeze-thaw cycles are expected to increase in all regions (Auld et al., 2007), which is a concern for all concrete dams going forward. Freeze-thaw cycles are known to lead to the deterioration of concrete. In warm temperatures, liquid water enters the pores in concrete. As temperatures drop below the freezing point, the water expands by about 9% in the winter. As the water expands, it induces tensile stresses in concrete. Once these stresses exceed the tensile strength, the concrete ruptures. Multiple freeze-thaw cycles can lead to cracking, crumbling and spalling (Portland Cement Association, 2019b). Therefore, a climate change-induced increase in the frequency of freeze-thaw cycles would lead to a more rapid rate of concrete deterioration in dams, which is cause for concern.

10.2.3.4 Sulphate Attacks

A final expected effect of climate change that will lead to accelerated concrete deterioration is an increase in the likelihood and magnitude of sulphate attacks on concrete. A sulphate attack occurs when concrete comes into contact with water containing sulphates, which react with concrete to form ettringite, an expansive product. The expansion due to ettringite formation imposes tensile stresses on concrete, which leads to cracking (Slag Cement Association, 2021). Climate change is expected to increase the concentration of sulphates in water, increasing the likelihood and intensity of sulphate attacks on concrete dams in the future. For example, in Plastic Lake, Ontario, studies have shown that sulphate in a stream increased significantly after a drought. During these periods of drought, the dry conditions in the wetland led to the oxidation of sulphur compounds, which were subsequently released during precipitation events (Aherne et al., 2006). Another study by Kerr et al. (2011) showed that 75% of catchments in the northeastern USA and southeastern Canada showed a response in the levels of sulphates based on seasonal drying. However, the effect of climate change on future sulphate levels in streams and rivers will vary by region, as each basin has a different response to seasonal drying (Kerr et al., 2011). For sulphate attack to occur, the water must contain sulphate at a concentration of at least 150 ppm. The severity of the sulphate attack increases with higher concentrations. In the prairies, certain waters contain sulphate at concentrations of up to 15,000 ppm, while in Ontario, certain waters contain sulphate at concentrations over 4,000 ppm (Swenson, 1971). Therefore, current concentrations in certain areas are already high enough to cause severe sulphate attacks in concrete dams. With the expected hydrological trends caused by climate change, these concentrations would only increase, thus increasing the severity of sulphate attacks. Furthermore, sulphate concentrations may increase in the future in regions where current sulphate levels are low enough for negligible risk and severity of sulphate attack. Therefore, sulphate attacks will likely be a concern in more regions in the future.

Extensive deterioration caused by thermal cracking, alkali-aggregate reactions, freeze-thaw cycles and sulphate attacks can have many adverse effects on dams and spillways. For example, cracks may begin as narrow surface cracks, but as these cracks widen and bridge the downstream and upstream faces of the dam, the reservoir water will begin to leak through (Hansen and Forbes, 2012). The direct implication of this is the loss of quality water from the reservoir. Furthermore, in hydroelectric dams, the resulting drawdown of the reservoir level would result in a lower gross head, reducing the power output. The reduction of water and energy supplies would have severe implications, particularly in the summer when there is an elevated demand for electricity and water. Another negative effect of cracking is that concrete permeability increases with the extent of cracking. This allows excess moisture and chemicals to enter the concrete, accelerating and amplifying the effects of alkali-aggregate reactions, freeze-thaw cycles and sulphate attacks (Wang et al., 1997). Furthermore, alkali-aggregate reactions, freeze-thaw cycles and sulphate attacks reduce the strength of the concrete, which may impact the overall structural stability of the dam. A study performed by Mohamed et al. (2001) investigated the development and effects of alkali-aggregate reactions on a concrete parapet wall of the Green Mountain Dam near the Colorado River, USA. The results showed that the alkali-aggregate reactions led to a 50% reduction in the strength of the dam structure over 50 years (Mohamed et al., 2001). Laboratory tests have shown that mechanical properties of concrete, in particular, cleavage strength, compressive strength and tensile strength, decrease with an increase in freeze-thaw cycles (Shang et al., 2014). Finally, laboratory testing has also shown that sulphate attacks combined with wetting and drying cycles, similar to the conditions that concrete dams are subjected to, cause a reduction in the compressive strength of concrete (Wang et al., 2021).

Alkali-aggregate reactions, freeze-thaw cycles and sulphate attacks have many detrimental effects on concrete dams, including the potential for leakage and increased permeability of concrete, leading to further deterioration and a reduction in mechanical properties affecting the overall strength and stability of dams.

10.3 Climate Change Adaptation Strategies

Existing dams must be retrofitted and upgraded to repair the impacts of climate change on the structural stability and material degradation of dams, while also mitigating any other negative effects. The mass and height of dams will need to be increased if accommodating higher reservoir levels is necessary. In addition, concrete will need to be repaired if the body or spillway of a dam is showing signs of deterioration or the concrete will need to be retrofitted to mitigate future erosion and damage caused by climate change. Existing alternatives for dam repair and retrofits and their ability to address the expected impacts of climate change will be discussed in the following subsections.

10.3.1 Strengthening Methods to Accommodate Increased Reservoir Level

10.3.1.1 Roller Compacted Concrete (RCC) Overlays

Roller-compacted concrete (RCC) is a dry, no-slump concrete mix—with the same elements as conventional concrete (PCA, 2019c)—that is transported, placed and compacted using earthmoving or paving equipment (Broucek and Satrapa, 2020). The advantage of using RCC over conventional mass concrete is the reduction of construction time and cost, along with enhanced performance (Avallone et al., 2019). These advantages favour the use of RCC for the upgrading of existing dams.

RCC can be overlaid over existing dams to improve the structural stability of dams under increased loads and to accommodate higher reservoir levels (Novak et al., 2004). The most common upgrade performed using RCC is dam heightening for overtopping protection (Hansen, 2003). RCC can also be used to repair dam breaches and construct downstream sections to increase the seismic resilience and sliding stability of dams (McDonald and Curtis, 1997). RCC overlays may also be used to increase spillway capacity or act as an emergency spillway due to the natural stepped shape of RCC placement.

There are many examples of RCC being used in dam rehabilitation projects worldwide. An example that emphasizes the advantages of RCC is the Tarbela Dam rehabilitation in Pakistan, which is regarded as the first modern application of RCC (URS Greiner Woodward Clyde, 2002). During the initial filling of the dam in 1974, an outlet tunnel collapsed washing away the surrounding rock and earth. 350,000 m^3 of RCC buttresses were placed within 42 days to replace the eroded rock and provide structural stability. The project held the record for the highest daily concrete placement rate for 28 years (Hansen, 2003). The rehabilitation of the Camp Dyer Diversion Dam near Phoenix, Arizona, USA, is another example of RCC being successfully used to upgrade the structural stability of a concrete dam. The dam had to be raised by 1.2 m above the original crest to provide additional storage, and buttresses had to be constructed to meet the safety requirements for dead loads and sliding resistance. Again, RCC was chosen as the optimal solution for these requirements due to its low cost and fast construction time (McDonald and Curtis, 1997).

10.3.1.2 Earth or Concrete Backing

Earth or concrete backing is a technique used to improve the stability of dams that is similar to the use of RCC overlays (Figure 10.1), and involves enlarging the profile of the dam, either using earthfill or rockfill (Novak et al., 2004) or concrete or masonry (CWC, 2018). The backing may be placed as a single continuous shoulder or buttress. Such a backing provides increased resistance to overturning and sliding through the increased mass of the structure. The added horizontal pressure from the backing acts on the existing dam body, which counteracts the hydrostatic force

(Novak et al., 2004). Moreover, the addition of a backing reduces the tensile stresses in the upstream face of the dam, improving the shear resistance of the dam body (Léger and Javanmardi, 2006). Concrete may also be placed as a downstream toe block, which enhances sliding stability, and it may also be used to expand the spillway apron in certain cases (Corns et al., 1988).

There are numerous examples of earth, concrete or masonry used to strengthen dams worldwide. The Barvi Dam in Maharashtra State, India, completed in 1976, required upgrades to enlarge its reservoir due to an increased industrial demand for water. To accomplish this, the dam was raised by 7.62 m and strengthened using a continuous masonry backing (Shukla et al., 2003). Another example is the rehabilitation of the upper Glendevon Dam in the United Kingdom. The dam was experiencing leakage through construction joints resulting in inadequate seismic stability. A downstream rockfill buttress was constructed to improve the seismic stability of the dam and increase its resistance to hydrostatic loads. The upgrading of the Matabitchuan generating station dam in Ontario is another example of this method. The dam was originally completed in 1909 and was upgraded in the 1920s. In 1992, an inspection showed that the dam was leaking due to the deterioration of concrete in the dam body. Multiple upgrades were performed, including the application of pre-stressing forces, the replacement of concrete and the addition of a rockfill embankment (Heidstra et al., 1996). In this case, rockfill was placed both on the upstream and downstream faces of the dam. The upstream embankment reduced leakage through the dam (Léger and Javanmardi, 2006), while the downstream embankment provided additional stability (Heidstra et al., 1996).

10.3.1.3 Post-tensioning

Post-tensioning involves applying pre-stressing forces to the body of the dam using tendons or bars (Figure 10.2). The anchor at the head of the tendons applies a compressive force distributed along the length of the tendon (CWC, 2018). This improves the dam's structural stability by enhancing resistance to overturning, sliding, tensioning and seismic loads. By applying the vertical post-tensioning force, the friction at the bedrock and concrete foundation interface increases sliding resistance (Xu and Benmokrane, 1996). The compressive forces can also mitigate further concrete deterioration by narrowing cracks in the dam body and compensating for tensile stresses that develop near concentrated forces on the dam (CWC, 2018). This method involves drilling holes in the crest of the dam, typically at intervals of 3 to 7 m, through the dam body and into the foundation. Pre-stressing strands or rods are lowered into the holes, and a grouted anchor is formed in the bedrock underlying the foundation (Novak et al., 2004). Various shapes of grouted anchors can be employed to accomplish varying bond strengths, such as straight shaft gravity grouted anchors, pressure grouted anchors and under-reamed, gravity-grouted anchors (Bruce and Littlejohn, 1997). The strands are then run through an upper anchor at the crest and stressed to the required pre-stressing load to maintain structural stability (Novak et al., 2004).

The main advantage of post-tensioning is that it is a structurally efficient and relatively economical method of raising dams. The alternative to raising a dam while ensuring structural stability is to thicken the dam body to increase its mass. Pre-stressing mitigates any concerns regarding the bond between the new concrete and the original concrete and the effects of that bond on the structural strength of the rehabilitated dam (Novak et al., 2004).

Xu and Benmokrane (1997) have highlighted five gravity dams in Canada that were strengthened using post-tensioning between 1985 and 1993. However, the upgrades were performed to improve seismic resilience rather than provide adequate structural stability to accommodate an increase in the probable maximum flood (Xu and Benmokrane, 1997). An example of a dam in Canada employing post-tensioning to raise the dam height is the Seven Mile Dam near Trail, British Columbia. The dam was initially built in 1980, was raised by 4 m in 1988, and post-tensioning was completed in 2003. 57 anchors and 92 strands with corrosion protection were installed in the upstream face to provide maximum overturning resistance. At the time, the anchors were the longest and highest capacity anchors in the world. A restressing system and dial gauge were installed, and the strands have been restressed many times since the completion of the project.

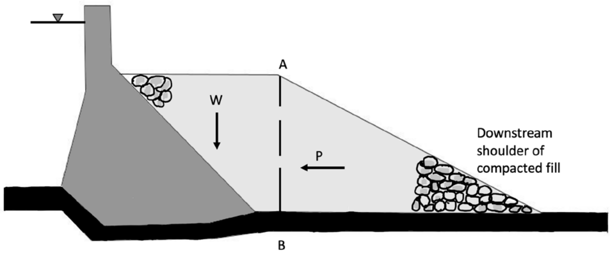

Figure 10.1 Additional forces imposed on a dam through the addition of a rockfill shoulder downstream (adapted from Novak et al. (2004))

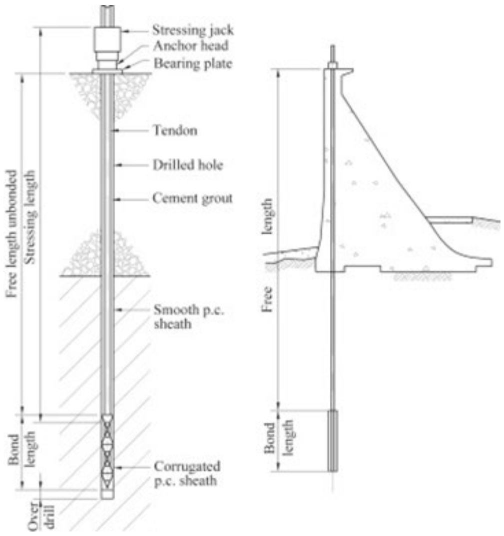

Figure 10.2 Schematic depicting dam post-tensioning (Brown, 2015; image licensed under CC BY-NC-ND 3.0)

10.3.2 Concrete Erosion, Cracking Repair, and Mitigation

10.3.2.1 Sealants

Much of the anticipated impacts of climate change on concrete deterioration in dams are aggravated by moisture. These impacts include alkali-aggregate reactions, freeze-thaw cycles and sulphate attacks. Sealants can be applied to cured dry concrete to reduce its permeability and mitigate these impacts. Sealants should only be applied to concrete surfaces that are generally in good condition and should not be applied to severely damaged concrete. There are three types of methods for sealing concrete surfaces. The first type involves using coatings to cover the entire concrete surface, such as epoxy or polyurethane. The second involves using low-viscosity crack sealants, such as low-viscosity epoxies or urethanes, which can be applied to the entire surface or locally on certain cracks. The final method involves using surface sealers, which repel water on the surface while leaving pores and cracks in the concrete open (USDI, 2015).

10.3.2.2 Thin Repairs

Thin repairs involve placing a layer of materials on the existing concrete surface between ¼ inch and 2 inches thick. Examples of materials and methods that can be used for thin repairs include the dry packing method, polymer concrete, epoxy-bonded concrete and packaged cementitious repair compounds. Thin repairs should only be used as a temporary repair measure in heavily deteriorated concrete or concrete that is susceptible to future deterioration. In some cases, the repair may even aggravate existing concerns. For example, in concrete subject to freeze-thaw cycles, additional moisture may become trapped between the existing concrete and the overlay, contributing to further freeze-thaw damages and de-bonding of the overlay. When the dam is susceptible to the alkali-silica reaction, the new concrete can introduce additional alkalis, accelerating deterioration caused by the alkali-silica reaction (USDI, 2015).

10.3.2.2.1 Dry Packing

The first type of thin repair is the dry packing method, which can be used to repair thin, dormant cracks or holes (USDI, 2015). A hole is drilled at the repair location using a sawtooth bit specifically designed for this type of repair, and the hole is cleaned and dried (Woodson, 2009). This step is essential to ensure a strong bond between the repair and the substrate (USDI, 2015). A dry pack mortar is then inserted into the hole in 10-mm-deep layers and tamped. The mortar should have a low water-to-cement ratio and contain sand that is finer than a No. 16 sieve (Woodson, 2009). An example of the dry pack method being applied in practice is the rehabilitation of the South Channel Dam in Post Falls, Idaho, USA. The dam was originally built in 1906, and the concrete body of the dam had become severely deteriorated since then. There were many voids in the body, some as deep as 0.6 m. The voids were repaired using the dry pack method to create an even surface, and the entire body was then faced with fresh concrete (Graeser and Jensen, 2016).

10.3.2.2.2 Polymer Concrete

Polymer concrete may also be used for thin repairs (USDI, 2015). Polymer concrete is a type of concrete where an organic polymer is used as the binder (American Concrete Institute, 2013). The most popular polymers used as binders are epoxy, polyester and methyl methacrylate (Vipulandan et al., 1988). The main advantage of using polymer concrete for repairs is that it quickly develops high strength and durability, making it optimal for quick repairs in severe conditions (USDI, 2015). The compressive, tensile, rupture and shear strength of polymer concrete is significantly higher than traditional concrete. Furthermore, polymer concrete is impermeable, which mitigates deterioration due to freeze-thaw cycles and sulphate attacks. Tests have shown that polymer concrete can withstand significantly more freeze-thaw cycles than conventional concrete and experiences negligible expansion due to sulphate attacks two years after exposure (Kirlikovali, 1981). The Old River, Low-Sill Control Structure rehabilitation near Baton Rouge, Louisiana, USA, is an example where polymer concrete was used in practice. The control structure includes spillways and a stilling basin, and is used to discharge water from the Mississippi River to the Red River.

10.3.2.2.3 Epoxy-Bonded Concrete

Another method that can be used for thin repairs is epoxy-bonded concrete where an epoxy bonding agent is applied to the existing concrete surface. An overlay of concrete is poured on top of the epoxy while still wet. The epoxy between the existing concrete and the overlay increases the bond strength between the two layers, increasing the durability of the repair. This method should only be used in situations where the substrate is of poor quality. In this case, the epoxy increases the bond strength between the two layers and increases the strength of the substrate (USDI, 2015). An important weakness of using epoxy-bonded concrete repairs, particularly in dams, is that the bond strength of the epoxy decreases significantly when exposed to moisture. This can lead to delamination of the overlay (Lau and Buyukozturk, 2010), which would render the repair ineffective. Although this method should generally be avoided where possible, there are examples of epoxy bonding being applied successfully in practice. One of those examples is the rehabilitation of the Wappapello Dam near Poplar Bluff, Missouri, USA.

10.3.2.2.4 Packaged Cementitious and Chemical Repair Mortars

The final class of materials that can be used for thin repairs are packaged cementitious and chemical repair mortars. These include a wide variety of materials, such as compounds containing Portland cement or magnesium phosphate. These compounds are proportioned to achieve various consistencies and levels of durability (USDI, 2015). The advantage of using these materials for thin repairs is that repair is quick and convenient due to quick setting times and strength gain compared with conventional concrete (Papas, 2014). An example of packaged mortars being used for repairs in practice is the rehabilitation of the Bambuna Falls hydroelectric project dam in Sierra Leone. The Bambuna Falls Dam is a rockfill dam where two concrete diversion tunnels and spillways were built to divert water during construction. The project was 80% complete by 1997, however, civil war in the area interrupted construction. The project resumed seven years later and, in 2004 and 2007, the existing structures were inspected. Among other issues, the inspections showed that the diversion tunnels and spillways had become severely eroded. A packaged fibre-reinforced shrinkage-free mortar was used to repair superficial erosion (deterioration of between 5 mm and 4 cm deep), primarily on the sidewalls of the tunnels. The packaged mortar was also used to completely surface the tunnels after the repairs were finished to ensure a smooth surface and high resistance to moisture and air (Petry and Bezzi, 2007).

10.3.2.3 Thick Repairs

Thick repairs are usually at least 6 inches thick (USDI, 2015) and used to repair serious deterioration. Examples of methods that can be used for thick repairs include conventional placement (Woodson, 2009), shotcrete and preplaced aggregate concrete (USDI, 2015).

10.3.2.3.1 Conventional Placement

In the conventional placement method, new concrete is used to repair the damaged area (Woodson, 2009). The deteriorated concrete is removed and the area is cleaned before concrete is placed on the damaged area and cured, either with or without formwork. This method can be used when cracking is at least 6 inches deep or 3 inches deep with exposed reinforcement (USDI, 2015). Conventional placement should not be used if there is no solid concrete for the repair to bind to or if there is an active threat of deterioration (Woodson, 2009). The advantages of this repair method are that it is low cost, it typically meets the requirements of most repair projects, and it generally works better than other methods (USDI, 2015). The quality of the repair is dependent on the quality of the concrete. It is recommended to use a low water-to-cement ratio and a high percentage of coarse aggregate to minimize thermal shrinkage cracks (Woodson, 2009). The abrasion resistance of the concrete can also be enhanced by using the hardest available coarse aggregates. High-performance concrete may also be used for this type of repair. High-performance concrete contains additional cementitious materials such as silica fume or superplasticizer, which significantly increase the strength and workability of the concrete and decrease its permeability (CWC, 2018). Another material that can be used with the conventional placement method is fiber-reinforced concrete, where fibers made of various materials such as steel or plastic are added to the concrete mix. The fibers increase the tensile strength of the concrete, which reduces shrinkage cracking, improves crack distribution and prevents longer-term cracking (Shclumpf et al., 2020).

The Loyalhanna Dam in Pennsylvania, USA, is a concrete gravity dam that was built in 1942. In 1986 and 1987, conventional placement was used to repair areas of spalling, leaching and cracking in the spillway crest. Damaged concrete was replaced with new conventional concrete to a depth of 4 inches. Subsequent inspections in 1990 showed that the repaired areas had minor cracking. However, they were generally in good condition and did not require further repairs (McDonald and Curtis, 1999). Silica fume has been successfully applied in practice to repair erosion damage in the spillway of the Kinzua Dam in Pennsylvania, USA (Graham, 1998). Prior to these repairs, a fiber-reinforced concrete overlay was used in the spillway.

10.3.2.3.2 Preplaced Aggregate Concrete

Preplaced aggregate concrete is another method that can be used for thick repairs. In this method, coarse aggregate is first placed into the formwork. The mortar is then injected into the voids within the aggregate (Lv et al., 2020). Injecting the mortar displaces any air or water in the voids, creating dense concrete (USDI, 2015). One advantage of this method is that it saves cement, which in turn increases concrete stiffness and reduces thermal shrinkage cracks. The reduction in cement content also lowers costs and increases environmental sustainability (Lv et al., 2020). Another advantage is that this method can easily be used in places where conventional placement is difficult (e.g., in underwater construction) (United States Bureau, 2015).

The preplaced aggregate method has been used many times in practice, however, its use has declined in recent years (USDI, 2015). One example that illustrates the enhanced durability of preplaced aggregate concrete is the rehabilitation of the Brandon Road Dam near Rockdale, Illinois, USA. This structure consisted of an embankment dam with a gated concrete structure that was initially completed in 1933. Rehabilitation was performed on the dam between 1984 and 1988, and included sealing eight gates with new concrete and repairing deteriorated concrete on the gated concrete structure.

10.3.2.3.3 Shotcrete

A final method that can be used for thick repairs is shotcrete, also known as gunite (USDI, 2015). In this method, a nozzle is used to spray the concrete onto the repair surface (CWC, 2018), which can be done using either the dry mix or wet mix method. In dry-mix shotcrete, the cement, sand and coarse aggregate are mixed with enough water to minimize dusting. The mixture is then shot through the nozzle using compressed air and hydrated with additional water from the end of the nozzle as it is being sprayed. In the wet-mix method, all components, including water, are added into the mix and then sprayed through the nozzle using compressed air.

There are many examples of shotcrete being applied in practice, and subsequent extensive investigations have been performed to determine the durability of such repairs. Heere (1995) investigated four dams in British Columbia that suffered freeze-thaw deterioration and were repaired with shotcrete. The repairs were found to be resistant to the local environmental conditions, however, there was some minor deterioration. The concrete on horizontal surfaces and concave corners had deteriorated and shrinkage cracks were observed. Based on these findings, it was recommended that steel fibers and silica fume be incorporated into the shotcrete and that placement be avoided on horizontal surfaces in future repairs (Heere, 1995).

10.3.2.4 Crack and Leak Repairs

Various methods exist to close cracks and stop leaks in concrete dams, including polymer injections using various materials such as epoxy resins or polyurethane and methacrylic acrylate resins. Another method that can be used to close cracks and stop leaks is adding additional reinforcement. These two methods can also be used in combination (USDI, 2015).

10.3.2.4.1 Polymer Injection

Polymer injection involves injecting polymers into a crack or leak at high pressure. There are two types of systems that can be used for polymer injection: rigid systems and flexible systems. For rigid systems, epoxy resin is typically used as the repair material. Rigid systems can be applied in dormant cracks but are not recommended for active (i.e., moving) cracks (Woodson, 2009). Cracks repaired with epoxy should be between 0.002 inches and 0.025 inches in width, however, a wider range may be acceptable depending on the viscosity of the epoxy. Furthermore, epoxy resins can bond to wet concrete making it suitable for use in dams and spillways (USDI, 2015). Flexible repairs can be used to repair active cracks, as the materials accommodate movement in the cracks (Woodson, 2009). Flexible materials that can be used for such repairs include polyurethane and methacrylic acrylate resins. Polyurethane can be used to repair cracks as narrow as 0.005 inches and methacrylic acrylates can be used to repair cracks that are even narrower. Only polyurethane should be used for structural repairs, while both materials can be used to seal leaks. Polyurethane resins, in particular, can be used to stop high-volume leaks. Furthermore, polyurethane resins are produced in various formulations, which cure into solids with different properties. Some resins cure into semi-flexible solids, while others cure into flexible foams. Flexible foams typically require the presence of water for curing and are therefore suitable choices for repairing dams and spillways (USDI, 2015).

Many examples exist of successful applications of such repairs in practice. For example, the San Esteban Dam in Northwest Spain is a concrete gravity dam that was built in 1964. In 1986, engineers confirmed that there were significant displacements in the crest of the dam, seepage on the downstream face and cracking caused by alkali-aggregate reactions. A proprietary epoxy resin injection system, known as RODUR, was used to bond the cracks. Since the completion of the repairs, no further cracking or displacement has been observed, and seepage through the dam has been reduced by 98% (Bruce and De Porcellinis, 1991).

10.3.2.4.2 Additional Reinforcement

Another method that can be used to repair cracks is the addition of new reinforcement on top of the existing concrete. Additional reinforcement can be used to increase the strength of existing concrete to withstand increased loads (USDI, 2015), including higher hydrostatic and sediment loads on dams due to climate change. Examples of reinforcement to close cracks are post-tensioning (pre-stressing) wires or bars and fiber reinforcement (USDI, 2015). Post-tensioning strands can be used to create additional compressive stresses in concrete, which cause cracks to narrow (Woodson, 2009). As previously discussed, post-tensioning can also be used to increase the structural stability of dams. Fiber mats may also be applied to concrete surfaces (USDI, 2015) to accomplish a similar function as pre-stressing strands.

10.4 Existing Climate Change Risk Assessment Tools for Dams

Owners and engineers require risk assessment tools to decide whether existing dams should be rehabilitated or upgraded, and which methods should be used for such purposes. Risk assessment involves quantifying risks by multiplying the probability of the occurrence of an event by the severity of the consequences if the risks occur. For example, the risk can be quantified in terms of expected dollars lost or human lives lost. The assessment can then be used to make the optimal decision resulting in the highest utility (e.g., aiming to minimize costs or loss of life) (Faber, 2002). In the specific context of dams, many risk assessment tools already exist. However, only a few of these tools incorporate climate change elements. Below is a description of the only two risk assessment tools for dams that consider the impact of climate change.

10.4.1 CSA S910

CSA S910 is a proposed standard under development by the Canadian Standards Association. CSA S910 is being developed at the request of dam stakeholders and it will provide them with the requirements and guidance for the assessment of dam vulnerability to climate change and the adaptations to improve the climate resilience of dams in Canada. A significant aspect of the new standard is providing guidance for adapting dams to be resilient to the effects of climate change by analyzing climate data and risk aspects. It will also provide guidance on climate change data sources and how to use them to determine the specific effects of climate change on dams (CSA Group, 2019).

10.4.2 A Guide to the Effects of Climate Change on Dams

Hughes and Hunt (2012) undertook a study commissioned by the UK Government Department of Environment, Food and Rural Affairs to investigate the effects of climate change on the maintenance and construction of dams in England and Wales. The project involved multiple aspects. First, a review of outputs from current climate models was undertaken, and an analysis was performed to determine the relevance of the outputs from these models and to evaluate how climate change may affect dams. Second, an investigation was performed to determine how climate change may affect dams, and an initial risk assessment framework and process for selecting adaption measures was developed. Third, case studies were undertaken to determine how theoretical climate risks translate into actual risks. Based on these investigations, a guide was developed for dam owners to address the effects of climate change on their assets (Hughes and Hunt, 2012). This discussion will focus on the evaluation and adaptation framework.

The assessment framework is similar to existing frameworks, except that it includes guidance on how to incorporate climate-related risks into the assessment. First, the potential failure modes are identified. Hughes and Hunt (2012) provided a framework for assessing failure modes. The failure mode assessment framework, design considerations, risk factors, maintenance factors, potential impact mechanisms and relevant aspects of climate change should be listed. Next, a risk assessment is performed based on impact mechanisms. The risk assessment step is divided into four sub-steps. First, the engineer should consider how impact mechanisms related to climate change would affect the failure modes that were identified in the first step of the overall framework. Second, climate change factors should be reviewed to assess their level of significance. Third, the level of risk for each significant impact is evaluated. Fourth, adaptations are recommended. This fourth step is broken down into a series of sub-steps, essentially prioritizing the types of adaptations that should be made. The following types of adaptations should be made in order of highest priority to lowest priority: change surveillance recommendations, change planned maintenance and operation, conduct capital works (i.e., spending money on upgrading the dam) and, finally, decommissioning the dam (Hughes and Hunt, 2012).

10.5 Gap Analysis, Future Directions and Workshop Feedback

It has become a reality that climate change and associated global warming are currently impacting the planet. Significant impacts of climate change could be the increase in extreme weather events such as floods, extreme temperatures and the frequency of heavy precipitations. Thus, these potentially devastating effects can highly endanger the safety of existing dams in addition to the other impacts on human beings and the environment. Although extensive research has been conducted to date, most studies have only focused on climate change's impact on the hydrological aspects of the problem (Bahls and Holman, 2014; Chernet et al., 2014; Novembre et al., 2015; Fluixá-Sanmartín et al. 2018). Thus, the application of this research on current dam safety is still uncertain (Bahls and Holman, 2014; Fluixá-Sanmartín et al., 2018).

10.5.1 Identified Gaps

(1) It is worth noting that the effects of a changing climate were not accounted for in the design stage of all existing concrete dams. Therefore, it is now vital to take the necessary mitigation measures and implement adaption techniques to minimize the adverse effects of climate change on concrete dams and their components (e.g., spillways, stilling basins, steel gates and penstocks). Nevertheless, minimal studies related to this problem have been conducted worldwide even though dam failure is always catastrophic and associated with fatalities and massive economic losses.

(2) The literature lacks studies related to the effects of climate change (e.g., increased temperatures, intense rainfalls and augmented hydrostatic pressure) on the stability and structural integrity of existing concrete dams.

(3) Climate change is expected to lead to the increased deterioration of concrete infrastructure in Canada in the future, but there has been little investigation dealing with the impact of climate change on concrete dams. The environmental conditions to which a concrete element incorporating alkali–silica reactive aggregates is exposed play a major role in dictating the progression and manifestation of the reaction and its damages. Alkali-silica reactions, which are known to be a serious problem for Canadian concrete dams, are affected by high humidity and high temperature. Methods to evaluate its damages need to be revisited, and preventive methods, such as the use of supplementary cementitious materials to replace part of the cement in concrete, need to be assessed for existing and new concrete dams to take into account the temperature rise. Combined effects of other deterioration mechanisms (freeze-thaw cycles, carbonation, corrosion, etc.) that are environmentally dependent have to be deeply investigated.

(4) It is unclear how climate change may impact the corrosion of a dam’s steel components, such as steel penstock and gates. The corrosion and defects of these elements could seriously affect the safe operation and use of a dam.

(5) The available literature completely lacks discussion or application of any concrete dam adaptation methods for a changing climate.

(6) The proper, continuous and updated managing process of the risk of failure is a necessary action during a dam's service life. However, existing risk assessment tools for dams do not incorporate elements of climate change, and they do not provide any specific guidance on which adaptations should be made based on the existing deficiencies or expected failure modes. According to National Research Council (2009) and Fluixá-Sanmartín et al. (2018), most risk assessment tools in the past have assumed stationary conditions in the variability of climate phenomena. Although Hughes and Hunt (2012) have developed a risk assessment tool incorporating the effects of climate change, they do not provide specific guidance on which adaptations should be made based on observed deficiencies or the expected effects of climate change. It would be beneficial to dam owners and engineers to be able to predict failure modes based on the location of the dam since the impacts of climate change are expected to vary across Canada. It would also be beneficial to provide a framework or recommendations on which adaptations should be used to address each deficiency or expected effect of climate

change. Participating in the development of CSA S910 should also be considered so that efforts to develop a risk assessment tool in Canada are not duplicated.

10.5.2 Future Directions

1. Investigating the impact of climate change on dam stability and structural integrity: Dams are subjected to direct and continuous environmental actions. Thus, climate change and associated global warming may greatly impact the safety and performance of existing concrete dams. These impacts could lead to dam failure, uncontrolled water releases caused by overtopping, and seepage through dams. Therefore, the impact of these effects on existing concrete dams needs to be investigated. Further details of this proposed project are outlined in Appendix A.6.1.
2. Development of strengthening or upgrading techniques for existing concrete dams: To address the concerns stated in gaps (1), (2) and (3) above, experimental and analytical research should be conducted to develop efficient and cost-effective climate change adaptation technologies for concrete dams. Research should focus on improving existing strengthening methods (e.g., post-tensioning, roller compacted concrete overlays and earth backing) used to increase the structural stability and height of a dam. Further details of this proposed project are outlined in Appendix A.6.1.
3. Development of a risk assessment tool that incorporates climate change effects: An extensive study should be carried out to develop a risk assessment tool that incorporates climate change effects to identify dams at risk. Risk assessment tools generally follow a process of gathering information, determining potential failure modes, finding the likelihood and consequence of each failure mode, and making recommendations to mitigate risks. Further details of this proposed project are outlined in Appendix A.6.2.
4. Damages caused by alkali-silica reactions, carbonation, induced corrosion and freeze-thaw cycles reduce the service life of concrete dams. The influence of relative humidity, temperature, wetting and drying on the development of alkali-silica reactions have to be evaluated. These factors exacerbate concrete deterioration and understanding the relationship between temperature, humidity rates and the deterioration of concrete dams is necessary for mitigation purposes. Methods used to assess the damages to concrete dams due to alkali-silica reactions need to be revisited and adapted to climate-change conditions:
    (a) The use of conventional and alternative supplementary cementitious materials (SCMs and ASCMs), including limestone calcined clay cement, as preventive measures for alkali-silica reactions in concrete, have to be investigated to develop binders with low carbon footprint for existing (reparation and maintenance) and new concrete dams. The cement replacement rates in concrete mixtures would reflect the influence of the temperature and humidity. Refer to Appendix A.6.5 for more details.
    (b) Data on concrete blocks made with reactive aggregates collected over more than 25 years in various environmental conditions (Ottawa, Canada [cold weather]; Austin, Texas, USA [hot weather]; and Treat Island, Canada [marine environment]) exist and would be used to develop a numerical model that will help predict

damages caused by alkali-silica reactions in concrete structures, including concrete dams. Refer to Appendix A.6.3 for more details.

10.5.3 Workshop Feedback

Participants noted that when it comes to concrete dams and the issues they face due to climate change, there is a hierarchy of importance, which is as follows: (1) durability; (2) serviceability; and (3) stability. It was advised not to jump too quickly into stability because a problem with serviceability will transform into a problem of stability; as such, these issues should be tackled in their order of importance. It was also recommended that a simplified tool could be developed to help owners cope. Participants echoed the importance of studying overtopping but noted that concrete dams have good resistance to overtopping. However, they also pointed out that while concrete dams can handle overtopping well, the equipment lying beneath the dams is not as robust. The participants proposed the development of a mitigation strategy that could accept overtopping, including some minor mitigation measures to protect equipment (e.g., adding fuses that will allow some spillways to release some water). More details can be found in Appendix B.

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11 Summary and Conclusions

Recognizing the need to adapt our new and existing infrastructure and operation procedures to withstand increased climatic loads and degradation mechanisms, the National Research Council Canada (NRC) has been collaborating with Infrastructure Canada to develop and revise codes, specifications, guidelines and assessment tools to advance adaptation solutions for Canadian infrastructure since 2016. Phase 1 of the Climate Resilient Buildings and Core Public Infrastructure (CRBCPI) initiative was undertaken at the NRC between 2016 and 2021 to integrate climate resilience into building and infrastructure design, guides, standards and codes. The target infrastructure types for the CRBCPI initiative included buildings, bridges, roads, rail, transit, and water and wastewater systems. In 2021, the NRC received approval to proceed with Phase 2 of the initiative, the Climate Resilient Built Environment (CRBE). In addition to the previously mentioned infrastructure types, dams are included in the scope of the CRBE initiative.

Dams retain enormous amounts of water and are designed to resist hydraulic loads, therefore, it is expected that the factors related to climate change that affect water flow will also affect dams. Unexpected interruptions in dam operations may lead to significant economic loss, while dam failures may be catastrophic. Historically, dam design, construction and operation have been carried out assuming stationary climatic and non-climatic conditions. In today's changing climate, the assumptions of stationary climatic baselines are no longer appropriate for long-term dam design and operation. The CRBE's Climate Resilient Dams (CRD) theme will focus on the development of technologies, procedures and guidelines for the adaptation of publicly-owned water dams to mitigate the adverse effects of a changing climate. It should be noted that tailing and mining dams are not included in the scope of the CRD project.

Water dams in Canada are owned by various entities such as federal and provincial governments, utilities and municipalities, agricultural districts, private organizations, and individuals. Canada does not have a federal regulatory agency or a unified program to guide the development of requirements for the safe management of dams. None of the provinces and territories had any specific legislation on dam safety until 1978 when the Province of Alberta established the first dam safety regulatory program in response to concerns due to a number of dam failures around the world. The main purpose of current dam safety regulations is to ensure that dams and their appurtenant and hydraulic structures are designed, constructed, maintained, operated and decommissioned with the best available technology and best practices. It should be noted that none of the currently published dam safety regulations reviewed within the scope of this project took into consideration or directly mentioned climate change. In order to address this gap, the objectives of this project were: (1) to identify knowledge gaps in the adaptation of Canadian dams to climate change; and (2) to develop future research directions for the NRC’s Construction Research Centre in the areas of climatic data requirements, operations, water quality, monitoring, geotechnical/structural aspects and material durability.

The gaps presented in this report are identified through literature review, interviews, discussions and consultations with dam experts and professionals, as well as a review of the current regulations. The following gaps are identified as potential research directions:

- **Quantification of climate change uncertainty**: The uncertainty associated with future projections of climatic data can be significantly high, particularly for compound parameters that include multiple climate variables, such as ice formation and flood. Due to the uncertainty in climate projections, particularly in long-term planning horizons, it is challenging to quantify the impact of climate change on water resources infrastructure such as dams. The quantification of climate change uncertainty and the share of each source of uncertainty are identified as gaps that need to be studied further.
- **Tools to forecast inflows and outflows:** Dam operation planning relies heavily on the prediction of inflows and outflows, both of which are influenced by the changing climate. Access to a tool that could provide operators with a robust inflow and outflow forecast, while accounting for the change in climate, could allow the consideration of long-term trends in short-term (i.e., daily) decision-making operations.
- **Operations optimization**: Changes in a dam’s inflows and outflows result in different dam operations. Their maintenance schedule, water allocation, sediment washing schedule and turbine operations are all impacted. Quantifying these impacts based on the expected unit variation in precipitation and temperature will help minimize the risks associated with climate change. The main objective here is to produce various climatic scenarios (both on precipitation and temperature) through model simulation and combine them with a state-of-the-art multi-objective optimization model while accounting for various dam operation and water allocation requirements. This tool, combined with the inflow and outflow forecasting tool described above, could quantify the impact of climate change on various dam operational requirements while accounting for the uncertainties associated with the changing climate.
- **Guideline for managing ice and break-up events**: Most of Canada is considered a cold climate area, where reservoirs and lakes are expected to freeze annually, yet no guidelines are available on how to manage dams during these events. A warming climate will increase the frequency of these freezing events. Therefore, quantifying the impact of icing and break-ups on various dam operations and the structural integrity of dams and providing general guidelines to dam owners and operators could help with the management of dams during these events.
- **Development of an integrated water quality model**: Climatic events that are expected to increase in frequency and intensity have varying impacts on dam reservoir water quality and the aquatic habitat within the dam. Notably, under specific circumstances, certain reservoir characteristics are highlighted as increasing the reservoir vulnerability to water quality issues. As for proposed future work, it is recommended that, based on a review of the literature, an appropriate dam reservoir should be selected for the development of an integrated water quality model. The developed model can be a useful tool for the assessment of climate change impacts on water quality in a dam reservoir under various future climatic scenarios. The model can be extended to other reservoirs based on the physical characteristics of reservoirs and characteristics of the watershed.
- **Satellite-based dam monitoring**: Dam health monitoring is an indispensable tool for ensuring dam safety conditions and maintaining operational functions during the service life of the dam. Many dams are located in remote regions of Canada, and are hardly

accessible to traditional surveying crews in the winter. Satellite-based monitoring techniques may offer a solution to this problem, however, it is still too early to trust observations from space as the only source of data for measuring surface displacements. Therefore, extensive research should be conducted to verify the suitability of the application of InSar technology in the practice of dam monitoring.

- **Risk assessment**: Managing the risk of failure is a necessary action during a dam's service life. However, existing risk assessment tools for dams do not incorporate elements of climate change, and they do not provide any specific guidance on which adaptations should be made based on the existing deficiencies or expected failure modes. It would be beneficial for dam owners and engineers to be able to predict failure modes based on the location of the dam since the impacts of climate change are expected to vary across Canada. It would also be beneficial to provide a framework or recommendations on which adaptations should be used to address each deficiency and each expected effect of climate change.
- **Structural stability and integrity of concrete dams**: Extensive research has been conducted to date on the impact of climate change on hydraulic structures. However, most studies only focused on the impact of climate change on the hydrological aspects of the problem. It is worth noting that the effects of the changing climate have not been accounted for in the design stage of currently operated concrete dams. Thus, the impacts of increased temperature and intense rainfalls on the deterioration mechanisms (e.g., concrete swelling due to alkali-silica reactions) and, in turn, stability and structural integrity of existing dam safety, are still uncertain. Therefore, it is important to study adaptive and preventive solutions to alleviate the impact of climate change on the stability and integrity of concrete dams.
- **Evaluation of potential acceleration in deterioration of concrete dams and preventative measures**: Climate change is expected to lead to an increase in the deterioration of concrete infrastructure in Canada, but there has been little investigation dealing with the impact of climate change on concrete dams. The environmental conditions to which concrete elements incorporating alkali-silica reactive aggregates are exposed to play a major role in dictating the progression and manifestation of the reaction and its damages. Alkali-silica reactions, which are known to be a serious problem for Canadian concrete dams, are affected by high humidity and high temperature. Methods to evaluate damages associated with alkali-silica reactions need to be revisited. Preventive methods, such as the use of supplementary cementitious materials to replace part of the cement in concrete, also need to be assessed for existing and new concrete dams to take temperature rise into account. Importantly, the combined effects of other deterioration mechanisms (freeze-thaw cycles, carbonation, corrosion, etc.) that are environmentally dependent must be investigated further.
- **Corrosion of penstocks and steel gates:** It is unclear how climate change may impact the corrosion of the dam’s steel components, such as steel penstock and gates. The corrosion and defects of these elements could seriously affect the safe operation and use of a dam. As such, it will be important to determine how climate change could affect the steel components of a dam.

- **Structural stability and integrity of earthfill dams**: The main gaps identified pertaining to this topic are: (1) the increased risk of susceptibility to seismic liquefaction of dams due to changes of effective stress of the soil; (2) the need to develop advanced methods based on artificial intelligence algorithms to predict variations in groundwater levels under various climatic conditions, and to assess the susceptibility of current slopes to future changes in climate; and (3) the need to identify critical conditions that may occur during the life of new dams as a result of climate change. Future effects of climate change, such as overtopping or damage to spillways due to increased precipitation, need to be addressed before the construction of new dams and as part of a retrofit of, or rehabilitation program for, existing dams.

The gaps identified above will be further evaluated and expanded upon through a workshop with dam industry professionals to be held in the 2022/2023 fiscal year where gaps, future research directions and projects will be finalized.

Appendix A - Proposed Projects

Appendix A outlines several proposed projects, along with their background, objectives, and methodology, to be executed under the NRC's CRBE initiative. These projects were proposed based on the findings of this study. It should be noted that not all the proposed projects will be executed. Projects elected for execution may not follow the methodologies and objectives described in this report, and modifications should be expected.

A.1 Future Climatic Data for Dam Design and Management

A.1.1 Background and Objectives

Canada is expected to be impacted by climate change, since it is warming at a rate that is approximately twice the global average, with even higher rates in the northern regions of Canada. The design and operation of dams and dam-related structures depend on several averages and extreme climatic loadings that are expected to change under future climatic conditions. Historically, the design and planning of dams has been based on historical climatic data. However, these parameters and their probability of occurrence are expected to change under a changing climate, which can impose higher risks to existing dam infrastructure. In addition to the structural behaviour, dam operation and water quality of dam reservoirs can be affected by climate change. Temperature, precipitation, ice condition, flood and drought are among such climate-related factors that can impact the operation of dams and the water quality of reservoirs.

The planning, design, safety and operation of dams as well as the water quality and aquatic habitat in dam reservoirs and the downstream reaches are expected to be impacted significantly by climate change. This demonstrates the importance of considering the impacts of climate change in the decision-making processes for dam management. However, the uncertainty associated with the future projections of climatic data can be significantly high, in particular for compound parameters that include multiple climate variables (e.g., ice formation and flood) and/or extreme climatic data. Due to the uncertainty in climate projections, it is challenging to quantify the exact impact that climate change will have, particularly in the long-term planning horizons required for specific water resource projects such as dams.

The main objective of the proposed project is to develop a tool that provides the following information for a selected number of dams across Canada:

(i) Projected changes in selected climatic variables and climatic parameters.
(ii) Uncertainty analysis and quantification of the share of each source of uncertainty in the future climatic data.

Such information can be integrated with the decision-making process and help implement the projected climatic data in practical applications related to dam management. For a number of dam locations across the nation, a tool can be developed to provide such information together with the downscaled projected climatic data.

A.1.2 Methodology

- Identifying and choosing the climatic data required for design, evaluation and management of new and existing dams.
- Selecting a number of dam locations based on the data available on the selected climatic data.
- Forming a multi-model, multi-scenario ensemble of projected climatic data. Based on the selected climatic data, as well as the scale and application, appropriate downscaling techniques may be implemented.
- Development of an uncertainty assessment model to quantify the share of the uncertainty for each climatic variable.
- Development of an interactive tool to explore, visualize and tabulate future climatic data.

A.2 Quantifying the Impact of a Changing Climate on Dam Operations

A.2.1 Background and Objectives

Climate change impacts not only the extreme hydrological events but also the averages. These would directly impact both the input and output flow of a dam. For instance, the change in precipitation would change the inflow, while temperature rise would result in an increased demand for water (i.e., water required for agricultural, municipal and environmental needs) and evaporation of water from the reservoir. As a result, every dam would be operated differently based on their specific requirements. The maintenance schedule, water allocation, sediment washing schedule and turbine operation of dams will all be impacted.

Anticipated impact: The proposed project fits under the “Dams” theme. The knowledge developed through this project will be a valuable resource for hundreds of small and medium dam operators in their struggle to manage their assets in preparation for the anticipated future of climate change. This project has the potential to save millions of dollars throughout the industry as well as reduce water loss and increase dam safety.

A.2.2 Methodology

The proposed study will quantify these impacts based on the expected unit variation in precipitation and temperature. The main objective is to produce various climatic scenarios (both for precipitation and temperature) through model simulation and combine them with a state-of-the-art, multi-objective optimization model while accounting for various dam operation and water allocation requirements. The outcome of this project will allow us to quantify the impact of climate change on various dam operational requirements while accounting for the uncertainties associated with the changing climate.

A.3 Climate Change Impacts on Water Quality in Dam Reservoirs

A.3.1 Water Quality of Dam Reservoir under Changing Climate

A.3.1.1 Background and Objectives

Ambient climatic condition is one of the major driving factors of water quality in dam reservoirs and downstream water. Reservoirs created by dams are used for several purposes, such as providing a source of drinking water and an aquatic habitat for flora and fauna. The water quality in reservoirs can be impacted by climatic variables such as ambient air temperature, precipitation, wind speed and cloudiness. This study aims to investigate the impacts of climate change on water quality in reservoirs and downstream reaches, and the implications for the source water and the aquatic ecosystem. This project aims to develop a two-phase three-dimensional hydrodynamic model, which will be coupled with a temperature and water quality model, to obtain potential projected changes in concentrations of selected water quality indicators. The results of the model for water temperature can also be used as an input for several applications, such as the assessment of the stability of in-ground permafrost supporting dams. The coupled water quality model for reservoirs will provide insights into the impacts of climate change on the quality of source water and the suitability of the aquatic habitat and will result in the development of guidelines for water quality in dam reservoirs.

A.3.1.2 Methodology

- Selection of appropriate dam reservoirs for collecting existing water quality data by conducting fieldwork. The selected dams will have representive characteristics to show the impacts of climate change on different types of reservoirs.
- Development of a hydrodynamic model to adequately capture the hydrodynamic characteristics of the reservoir during various flow/operational conditions.
- Development of a water quality model coupled with the hydrodynamic model in order to simulate the water quality parameters in the reservoir.
- Simulating various flow/water quality scenarios under different climate change scenarios using the developed model to understand the impacts of climate change on water quality in dam reservoirs.

A.3.2 Impact of Climate Change on Fish Habitat Downstream of Dams

A.3.2.1 Background and Objectives

Water temperature is a major controlling factor affecting the metabolic rate, growth and reproduction of fish. Spawning and egg development are particularly sensitive to temperature fluctuations as these processes require very specific temperatures. Increases in water temperature of only 2°C cause physiological disruptions that decrease reproductive success. Therefore, it is critically important to understand the thermal habitat of the reservoir in order to predict the thermal resilience of fish species to climate change. Physiological differences in response to temperature changes can be used to categorize fish species into cold, cool and warm water species assemblages. In particular, the thermal habitat of cold-water species is at risk under the current climate warming trends. Nearshore habitats are the main site of spawning, egg development and critical growth during the first year of life. However, because nearshore habitats are complex, their thermal profile is not well studied. Nearshore fish habitats above and below dams may be particularly vulnerable to climate change because it is also subject to rapid temperature changes due to the peaking and ponding of dams. The objectives of this study are to: (1) create a predictive model of nearshore water temperature based on climate scenarios (long-term trends), peaking and ponding scenarios (short-term trends), and empirical data (continuous temperature samplers); and (2) relate predictive temperatures to the thermal and physiological requirements of individual fish species living in the St. Lawrence River.

A.3.2.2 Methodology

- Collection of water temperature data using sensors currently installed at the dam intake (River Environment and Sensor Observation Network); 100 continuous temperature loggers deployed at nearshore sites; boat surveys using continuously logging multi-probe sondes; and thermal maps obtained by drone surveys. Drone surveys will be conducted at a subset of nearshore sites where the temperature loggers are deployed. Data will be collected across multiple seasons during a one-year study period.
- Gathering and organizing existing data on thermal habitat and physiological requirements for spawning and growth of various cold, cool and warm water fish species (DFO documents, already organized from a previous project). Data will focus on temperature metrics describing reproduction (i.e., optimum spawning and egg development temperature) and growth (i.e., optimal body growth temperature, growing degree days, growing season length). Thermal requirements of each species will then be compared to the temperatures that the fish are currently experiencing (measured using sensors and nearshore temperature loggers) and the temperatures predicted by the model under various climate and flow scenarios.
- Using existing hydrodynamic models to generate the flow hydrodynamics for various flow scenarios.
- Development of an artificial intelligence model for the prediction of water temperature based on ambient climatic conditions and river hydrodynamics. This model will increase our understanding of the effects that peaking and ponding of dam reservoirs have on the relationship between the temperature of the main stem of the river and the fine-scale temperature of nearshore habitat. This model can then be used to predict nearshore temperatures based on climate-change scenarios.

A.4 Satellite Monitoring of Dams

Space-borne Interferometric Synthetic Aperture Radar (InSAR) technology is an innovative approach showing promise, with several benefits over other technologies. For example, InSAR technology can be used remotely to provide accurate measurements to the millimeter over the entire structure during the day or night, under adverse weather, and does not necessitate the installation of complex instruments on the structure.

A comprehensive study will be conducted to assess the reliability of the persistent-scatterer (PS)-InSAR approach in dam monitoring and will include measuring the displacements of several Canadian dams from space. The displacement readings collected will be validated by comparing them with other available displacement measurements determined by traditional or advanced geodetic data records. The behaviour of the dams selected in this proposed study will also be investigated using finite element (FE) modeling, and the results will be checked against the PS-InSAR measurements. Furthermore, an extensive literature review related to PS-InSAR technique applications in dam monitoring will be performed.

A.4.1 Background and Objectives

The suitability of the PS-InSAR approach in dam monitoring will be investigated extensively. More research related to the application of this novel technology in dam monitoring should be carried out.

A.4.2 Methodology

This study will include measuring the displacements for several Canadian dams from space using the InSAR technique. Two of the dams will be the Hilton Falls and Kelso dams located in Milton, Ontario. The displacement readings collected will be validated by comparing them with other available displacement measurements obtained by traditional or advanced geodetic data records. The behaviour of the dams selected in this proposed study will also be investigated through FE modeling, and the results will be checked against the PS-InSAR measurements. Furthermore, an extensive literature review related to PS-InSAR technique applications in dam monitoring will be performed.

All measurements collected by the various sensors installed during the dam monitoring process should be compared to the corresponding parameters obtained from numerical modeling of the dam structural behaviour. This integration is significant for investigating dam performance during dam construction and post-construction stages. A good agreement between numerical modeling (e.g., finite element methods (FEM)) and actual field results suggests a correct design. In contrast, any deviation between the two sets of results mentioned above will also be useful in calibrating the numerical models for use in future projects. According to Gikas and Sakellariou (2008) and Scaioni et al. (2018), FEM is one of the most popular dam modeling approaches due to its ability to handle complex geometries and adapt to specific geological and boundary conditions.

A.5 Climate Change Impacts on Embankment Dams

A.5.1 Background and Objectives

The main objectives of the proposed research work would be: (1) to identify the main mechanisms for potential geotechnical stability issues of dams due to changes in precipitation regimes caused by climate change; and (2) to develop preliminary adaptation measures for dam stability and enhanced climate change resilience. The aim is to develop an early warning system based on precipitation and pore water pressure data. Early warning systems for dam slopes and for landslides upstream of the dams may prove a valuable tool for damage prevention. Early warning systems for these purposes have already been in use in Japan since the 1980s (Osanai et al., 2010) and in the Seattle area of the USA since 2002 (Baum et al., 2005; Baum and Godt, 2010). The early warning system approach is meant to be used in scenarios where scarce data is available to develop reliable site models and it relies on the development of a “Critical Line”, which is generated within a space defined by a “short-term rainfall index” and a “long-term rainfall index”. These indices are generally based on defining a minimum threshold for landslide triggering based on rainfall intensity and duration analysis (for the short-term rainfall index), as well as an antecedent water index (for the long-term rainfall index) calculated on the basis of the cumulative rain for the previous 3 days as well as rain from the previous 15 days (Chleborad, 2000; 2003; 2006).

A.5.2 Methodology

The analysis of the minimum threshold for landslide triggering upstream of dams requires the study of historical data where recorded landslide events can be associated with the corresponding rainfall intensity as well as antecedent precipitation conditions. Such a system will need to be calibrated based on the historical data that it is based on, which reflects not only the precipitation conditions that triggered the landslides, but also the geological conditions where the dams are located.

Since earth dams are also susceptible to slope failures, the above-mentioned early warning systems could also be applied to the dams themselves, but in such cases, the data used in the derivation of the required indices would have to be based on historical dam failures using similar construction methods and internal structures. Back analysis of the geotechnical stability of the dams will be used to estimate conditions at failure. In addition to the geotechnical data from a sample of representative dams to be studied, the proposed set of data to be used in this project will incorporate environmental data from the region of study as well as InSAR satellite images of the area of interest. Artificial intelligence algorithms will be used to evaluate the data and to identify patterns that may be used to develop the early warning systems.

A.6 Climate Change Impacts on Concrete Dams

A.6.1 Update of Design Methodology and Climate Adaptation Technologies for Concrete Dams

A.6.1.1 Background and Objectives

Alkali-silica reactions are known to be a serious problem for Canadian concrete dams, and these reactions are affected by high humidity and high temperature. Methods to evaluate the damages caused by these reactions need to be revisited, while preventive methods, such as the use of supplementary cementitious materials to replace part of the cement in concrete, need to be assessed for existing and new concrete dams to take temperature rise into account.

The design methodology for existing dams needs to be updated by incorporating climate change factors. Elementary design methods and modern design methods (e.g., trial load methods and finite element methods) will be performed and their results will be compared. In addition, the most efficient and cost-effective climate change adaptation techniques for existing concrete dams will be proposed.

A.6.1.2 Methodology

Data on concrete blocks made with reactive aggregates have been collected for over 25 years in various environmental conditions: Ottawa, Canada (cold weather); Austin, Texas, USA (hot weather); and Treat Island, Canada (marine environment). These data would be used to develop a numerical model that will help in predicting the damages caused by alkali-silica reactions in concrete structures, including concrete dams.

Investigate the adverse effects of climate change on concrete through experimental testing and 3D finite elements (FE) modeling. The effects of increased hydrostatic pressure and temperature due to climate change on concrete dam stability and permissible concrete stresses will be explored.

A 3D FE simulation of the structural behaviour of several strengthened concrete dams (case study) will be performed. Different strengthening techniques will be explored and compared.

A.6.2 Development of a Risk Assessment Tool for Dams

A.6.2.1 Background and Objectives

Develop a risk assessment tool that considers the impacts of climate change and provides guidance on which repair and upgrading methods should be used.

A.6.2.2 Methodology

Carry out an extensive literature review and incorporate climate factors in a developed risk assessment tool.

A.6.3 Model Concrete Deterioration due to Alkali-Silica Reactions

A.6.3.1 Background and Objectives

Model concrete deterioration due to alkali-silica reactions and incorporate this model in FE simulations of the structural behaviour of concrete dams to identify the effect of alkali-silica reactions on dam safety.

A.6.3.2 Methodology

Conduct an extensive experimental and analytical program.

A.6.4 Evaluation of Impacts of Climate Change on the Components of Hydropower Dams

A.6.4.1 Background and Objectives

Study the effects of climate change such as higher than historical temperature levels and diffrentials coupled with corrosion on steel gates and penstocks.

A.6.4.2 Methodology

This will be achieved through Finie Element Modeling. Some testing/field studies may be needed.

A.6.5 Limestone Calcined Clay Cement (LC3) for Canadian Concrete Dams' Durability

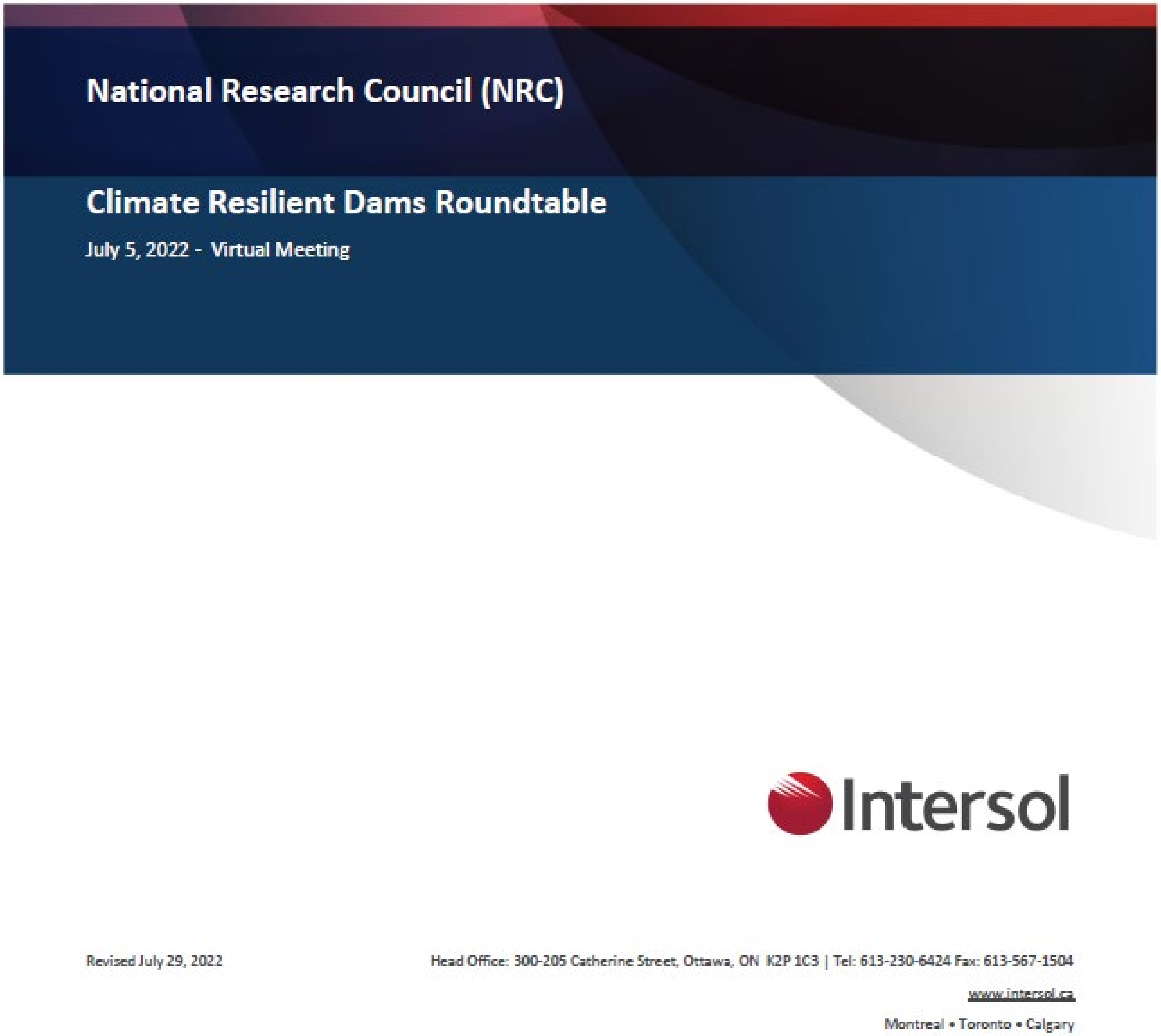
A.6.5.1 Background and Objectives

The objective of this project is to investigate the feasibility of the development of a low-carbon alternative to standard Portland cement using the synergetic effect from the combination of the limestone and calcined clays from local Canadian sources to improve the durability of Canadian concrete dams.

A.6.5.2 Methodology

Conduct an extensive experimental program.

Appendix B - Intersol Report



National Research Council (NRC)

Climate Resilient Dams Roundtable

July 5, 2022 - Virtual Meeting

Revised July 29, 2022

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B.1 Background

In response to the need to adapt existing infrastructure to the effects of climate change, the National Research Council Canada (NRC), in collaboration with Infrastructure Canada, is developing updated codes, specifications, guidelines and assessment tools to advance adaptation solutions for existing and new infrastructure under the Climate Resilient Built Environment (CRBE) initiative. As part of the CRBE initiative, the NRC is conducting dam-related research that will focus on developing technologies, procedures and guidelines for the adaptation of dams to the effects of a changing climate.

On July 5, 2022, the NRC held a workshop aimed at bringing together relevant stakeholders from the public, private and academic sectors to formulate a research agenda that meets the needs of dam owners, operators and regulators. The goal of the workshop was to identify information needs, highlight critical knowledge gaps and define appropriate research responses to close these gaps.

Following introductory presentations on the CBRE initiative and proposed projects, participants offered input on proposed research projects in four themed breakout groups: (1) Climate Change Quantification; (2) Ice; (3) Operations; and (4) Structural/Geotechnical. An online input platform offered an additional way for participants to provide feedback.

This report captures stakeholder input from the roundtable. A standard set of three questions was posed for each research project discussed in the breakout sessions. Where a particular question is not included in the summary of that session, no input was provided by the participants.

B.2 Context Setting

B.2.1 Introduction to the NRC’s Climate Resilient Built Environment Initiative

Marianne Armstrong, Initiative Lead, NRC, provided an overview of the dams theme of the CRBE initiative. The initiative has five broad goals:

- Generating knowledge
- Supporting evidence-based decision making
- Enabling regulation
- Advancing technical solutions
- Building capacity in Canada and abroad

B.2.1.1 Participant Responses

In the online input platform, a participant expressed concern that referring to “resilience” in physical infrastructure such as dams is misleading because the infrastructure cannot respond to events or repair itself. It would be more accurate to refer to resilience in the system in which the infrastructure functions. This view can help frame the thinking around how dams and the related systems can be impacted by climate change and the vulnerabilities that exist.

Another respondent noted that one of the projects in the NRC's Industrial Research Assistance Program (IRAP) is developing technology for the real-time monitoring of critical infrastructure such as dams and bridges, which could be explored.

B.2.2 Proposed Research Projects

A series of presentations summarized the proposed CRBE projects from the NRC's Construction Research Centre and Ocean, Coastal and River Engineering Research Centre.

B.2.2.1 Participant Responses

It was suggested that there could be a general approach to the research topics that focuses on the identification, assessment and mitigation of vulnerabilities of dams related to the effects of climate change. Examining how climate information and projections can increase or elevate the vulnerabilities of a dam or dam system would be valuable.

Participants supported the idea of combining in situ sensors for real-time remote monitoring with satellite imaging. It was noted that commercial services for satellite-based monitoring and tools for forecasting inflow and outflow are widely available. Participants also wanted greater clarity on why mining and tailings dams are to be excluded from the initiative.

B.3 Climate Change Quantification

B.3.1 Quantification of Climate Change Uncertainty

B.3.1.1 a. Would the research project proposed contribute to dam operations?

The group acknowledged that the project addresses a fundamental challenge in dam design and operations, but it covers a broad area, and the specifics will need to be nailed down.

There was a suggestion that the international climate change science community continue to work on improving climate data and reducing uncertainty. What is needed more urgently by Canadian dam industry practitioners is guidance on how to make use of this world-class information.

B.3.1.2 b. In your opinion, are there any gaps in our current thinking?

Participants noted that the project should take into account the differing needs for climate data of operations versus design. Operations are likely interested in average changes in climate variables (e.g., changes in monthly means of precipitation), while design is interested in extreme and rare events (e.g., 1 in 1000 year flood), which are often less accurately captured in climate models.

A gap was identified with respect to policy. In many provinces, dam design follows a legislative driver. Without the right drivers to embrace uncertainty and insert it into the design, there may be a shortfall in the practical incorporation of climate change data.

B.3.1.3 c. Is there anything else you want to bring to our attention?

One participant said that the quantification of uncertainty as a barrier to implementing climate change resilience is not the core issue. Rather, the focus should be on what should be done in practice. How do we establish the design for a piece of infrastructure given the uncertainty that we have? How do we embrace the uncertainty in design?

A proposed output for the project was training for how to introduce a climate change perspective into engineering. It was also suggested that it would be more valuable to develop a framework or process for the quantification of uncertainty in climate projections and guiding principles for incorporating climate change data than to produce a specific tool that may be highly site-specific.

B.3.2 Guidelines for Estimating Design Floods to Support Climate Resilience of Dams and Levees in Canada

B.3.2.1 a. Would the research project proposed contribute to dam operations?

There was general agreement that this would be a valuable project and would contribute to dam operations, especially for small asset owners. No national guidance is available for the estimation of probable maximum precipitation and probable maximum flood and, in particular, on the integration of climate change information with design flood estimation methods. However, some participants thought there could be redundancy with Canadian Dam Association efforts.

B.3.2.2 b. In your opinion, are there any gaps in our current thinking?

It was suggested that the joint influence of extreme precipitation and temperature on dam and levee operations be considered.

B.3.2.3 c. Is there anything else you want to bring to our attention?

A number of recommendations were offered regarding what the guidelines should include:

- Guidance on the use of data, flood estimation procedures and performing a resilience assessment
- Guidance on calculating the return storm precipitation depth and how to build the storm hydrograph
- Meteorological data acquisition (source, model, extraction tools, etc.)
- Statistical calculation (method, distribution used, calculation tools, etc.)
- Methods for the integration of climate change data
- How to account for uncertainties in climate change projections

B.3.3 Development of an Integrated Water Quality Model

The group ran out of time to discuss this project. In the online input platform, the suggestion was made to make the project applicable to a broader context by considering which aspects of water quality are vulnerable to climate change and future scenarios that would lead to the greatest impacts on dam reservoir characteristics.

B.4 Ice

B.4.1 Monitoring and Prediction of Ice Jams

B.4.1.1 a. Would the research project proposed contribute to dam operations?

There was agreement that ice jams cause serious problems in some parts of Canada in terms of flooding and potential dam breach. Events can occur very rapidly. The impact of ice jams can be structural but also operational because they affect water levels and can reduce power generation. Predictive tools would allow for the pre-emptive release of more water through increased flow at the dam.

It was noted that the Canadian Dam Association classification does not emphasize ice as much as it should.

B.4.1.2 b. In your opinion, are there any gaps in our current thinking?

Participants proposed a number of ways to gather further information:

- Surveys of facilities
- A review of the current state of practice
- Forensic analysis of failure events

B.4.1.3 c. Is there anything else you want to bring to our attention?

Predictive tools would have to be probability-based because river ice events are complex. Suggestions for possible predictive tools included:

- Maps to identify areas of river systems prone to ice jams
- A version of the flood predictor model for ice
  - The Lower Churchill River has a winter model that predicts ice jams using satellite images of ice cover and real-time buoy information
  - Satellite and weather data could be analyzed by a predictive artificial intelligence system to assess the risk
- Development of best practice guidelines

B.4.2 Monitoring, Prediction and Management of Frazil Ice

B.4.2.1 a. Would the research project proposed contribute to dam operations?

The primary issue with frazil ice is its impact on power generation. Participants said that it would be beneficial to determine how climate change could impact the known conditions for frazil ice or alter the vulnerabilities in the water supply or power generation system (e.g., how a changing climate influences river ice characteristics and what this means for dam and system operation).

B.4.2.2 b. In your opinion, are there any gaps in our current thinking?

Some locations are more prone to frazil ice than others. Past frazil ice events could be correlated with current climate conditions to develop predictive models.

B.4.2.3 c. Is there anything else you want to bring to our attention?

Several mechanisms for dealing with frazil ice were noted:

- Halting operations until a stable ice cover has formed
- Ice booms
- Replacing metal trash racks with plastic trash racks
- Nature-based solutions for dealing with erosion, such as using vegetation to stabilize riverbanks

B.5 Operations

B.5.1 Operational Optimization/Tools to Forecast Inflows and Outflows

B.5.1.1 a. Would the research project proposed contribute to dam operations?

Participants mentioned that some inflow prediction models are currently in use by the industry. Furthermore, short-term outflow prediction tends to be case-specific and may not be as useful in the context of climate change. A different approach would be to look at the issue from the perspective of a Failure Modes and Effects Analysis (FMEA) rather than operations. The development of scenarios, potential adaptation practices, etc., that could feed into an FMEA for validation of operating and design decisions could be useful as planning tools.

B.5.1.2 b. In your opinion, are there any gaps in our current thinking?

It was suggested that tailings dams be added to the study.

B.5.2 Computer Models for Operational and Structural Adaptation of Dams to Future Climate Conditions

B.5.2.1 b. In your opinion, are there any gaps in our current thinking?

The project should consider the vulnerabilities in the dam or dam system that are impacted by climate change, and vulnerabilities that could require adaptation in the future (structural or operational). Computer models of these options can be supportive tools. Suggestions were made to focus more on short-term (i.e., daily) and mid-term (i.e., El Niño) events and their impact on operations rather than on the design event.

B.5.2.2 c. Is there anything else you want to bring to our attention?

Participants recommended considering the nature of site-specific issues related to dam operation and collaborating with more owners and operators to get a richer sample of case studies.

B.5.3 Debris-flow Risk Management

The group did not have time to discuss this project fully.

B.5.3.1 b. In your opinion, are there any gaps in our current thinking?

It was recommended that the project account for different types of debris and their potential for blockage.

B.6 Structural/Geotechnical

B.6.1 Smart Monitoring for Dams – Satellite-based Monitoring

B.6.1.1 a. Would the research project proposed contribute to dam operations?

Participants said the stability of aging dams is an emerging issue for the industry as many major dams were constructed before modern dam design practice evolved. Any deformation in the body or foundation of the dam will affect the performance of the structure. It is important to detect and prevent any larger deformation. Industry needs more tools to address this issue.

It was suggested that the name of the project should be changed to clearly indicate that a combination of satellite imagery and sensor data would be employed. There was also a comment that, because a good deal of work has been done in this area, the project should focus on expanding the current knowledge base.

B.6.1.2 b. In your opinion, are there any gaps in our current thinking?

Participants raised a number of points for consideration:

- Sedimentation, scouring and erosion: Greater and/or more frequent flow extremes through dams can significantly affect the structural integrity of the dam via increased scouring/erosion on the existing dam features intended to mitigate these effects (e.g., concrete dam apron, scour protection mattress) and, more importantly, on the unprotected areas of the river bed immediately adjacent to the dam/scour mattress. The “old” footprint is no longer sufficient and riverbed scour becomes the mechanism that causes these features to fail. Further research was proposed on how to best retrofit existing dams to deal with these failure mechanisms safely and efficiently.
- Radar monitoring is not a mature area and guidelines are required.
- High-quality data will be an important consideration. In situ sensors were suggested for calibration.
- Structural stability and integrity are broad terms that may mean different things to different people and it will be important to define these terms clearly before scoping the research.
- Consideration should be given to timely post-event monitoring in addition to routine monitoring.
- Will stability be defined in terms of factors of safety or deformation?

B.6.1.3 c. Is there anything else you want to bring to our attention?

Interest was expressed in allowing the industry to contribute to this research project, perhaps through a technical committee.

B.6.2 Evaluation of Potential Acceleration in Deterioration of Concrete Dams and Preventative Measures

B.6.2.1 b. In your opinion, are there any gaps in our current thinking?

Participants indicated that the effects of sedimentation and scour of the riverbed should be considered. Riverbed scour immediately adjacent to the structure and/or scour mattress is a common issue and leads to the structural instability of the dam.

B.6.3 Structural Stability and Integrity of Concrete Dams

B.6.3.1 a. Would the research project proposed contribute to dam operations?

Participants indicated that this project is very important, particularly in relation to older, aging dams built prior to the implementation of modern design standards.

B.6.3.2 b. In your opinion, are there any gaps in our current thinking?

There was a suggestion that scour issues related to the riverbed and scour mattress be considered in the scope of the project.

B.6.3.3 c. Is there anything else you want to bring to our attention?

Several issues were raised, including:

- Flooding due to increased precipitation: Resistance to overtopping is important in relation to the loss of electricity for operating the gates. Increasing the height of the dam could address overtopping.
- Alkali-silica reaction affects the gates, especially in winter.
- Durability, serviceability and stability are all issues that should be considered.

It was also noted that a system for real-time monitoring of dynamic displacement is available through an NRC IRAP project.

B.6.4 Structural Stability and Integrity of Earthfill Dams

B.6.4.1 b. In your opinion, are there any gaps in our current thinking?

The issue of liquefaction due to changes in the effective stresses in dams was raised. In response, it was pointed out that dynamic-displacement real-time monitoring would be a great way to monitor liquefaction-related issues for early warning opportunities. However, another participant noted that liquefaction is a small-strain mechanism and, as such, by the time there is any expression of displacement (large-strain mechanism), it is already too late. The perception that liquefaction can be predicted using displacement monitoring and used as an early warning system is a misconception.

Another concern was the need to clarify how climate change poses a structural risk to earthfill dams, aside from the hydrological changes. For example, what is the mechanism by which climate change would affect effective stresses? Defining specific hazards and mechanisms would provide a method by which engineers could then develop designs to resist the specific hazards.

Other issues identified briefly include internal zoning, internal erosion, changes in shearing and effective stress behaviour, surface erosion and creep behaviour.

B.6.4.2 c. Is there anything else you want to bring to our attention?

The issue of not including mining and tailings dams in the initiative was raised again.

B.7 Additional Projects and Other Research Topics

Participants were given the opportunity to comment online on projects not covered in the meeting agenda and to recommend other research gaps or topics to be addressed.

B.7.1 Enhancement of Spillways Conveyance Capacity

Recommendations on aspects to consider include:

- How to identify vulnerabilities in the dam system and its operation leading up to the design event (i.e., access challenges during a flood event that is below the design event).
- How to mobilize additional spill capacity for any reason even if the design capacity has not been exceeded (i.e., transmission capability compromised, the gate is frozen or out of service, changes in seasonal spill requirements, etc.).

B.7.2 Nature-based Solutions for Improving Climate Resilience of Dams and Embankments

It was suggested that nature-based solutions may be a good option for addressing legacy infrastructure. For example, many concrete dams could be anchored or may inherently allow for overtopping without failure. How could we allow earth dams to be overtopped without failing?

B.7.3 Risk Assessment

Risk assessment was seen by some to be the most important of all the proposed projects because climate change presents many uncertainties, and risk-based decision making is needed to deal with uncertainty. Guiding practitioners on how to appropriately conduct a climate change risk assessment for dams will be highly beneficial and will identify other follow-on research needs.

Specific recommendations for the project included:

- Build a knowledge base of dam failure modes that are related to climate change: This could be based on the FMEA approach, which is fairly standard in the dam safety industry. Include identification and assessment of vulnerabilities of dams and the dam system that are impacted by climate change.
- Real-time and trend analysis for critical dam structure deformation, dynamic displacement, and stress can provide a risk assessment framework. Consider developing structure health monitoring systems.

The development of a risk assessment tool that integrates the effects of climate change on existing dams is already one of the potential projects proposed by the NRC’s Construction Research Centre to be commenced this year. This project aims to identify dams at risk and take appropriate mitigation measures.

B.7.4 Other Research Gaps or Topics

Several additional research gaps and topics were proposed:

B.7.4.1 Examination of Climate-Based Changes Observed Within the Design Envelope

Most of the observable climate change impacts/events are not that extreme in the context of dams. For example, the loading characteristics on a dam or a dam's operation may be influenced significantly by changes in climate, but none of the events on their own would be considered a design event or extreme event. Changes to consider could include mid-season temperature swings, longer-term drought or flood cycles, spillway operation in winter, debris loading of dams after a forest fire, etc. These more frequent impacts could result in a slow erosion of performance or functionality and could impact how the dam or dam system is able to respond to a subsequent extreme loading event in the future.

B.7.4.2 Introducing Climate Change and Climate Information Tools in Training Programs

Most new graduates still have a very limited understanding of these concepts.

B.7.4.3 Publicly Accessible Data on Dams Without a Clear Operator (Orphan Dams)

Compiling data into a central inventory to track these dams and the properties they would affect downstream would be valuable for the incorporation of data into insurers' and other key stakeholders' risk assessments and modeling. The state of the dam upkeep or lack thereof would also be of interest as it would help prioritize future mitigation priorities for reducing risk.

B.7.4.4 Dam and Dam Safety Operations and Regulations

These safety operations and regulations are an important consideration for the research and resilience of dams. This would be more of a policy review. Are existing regulations and guidelines a barrier to the adaptation or incorporation of climate change? Do the right regulatory and financing environments exist, and what incentives could be included to move the bar forward?

B.7.4.5 The Supply and Availability of Data and Expertise

Do we have the right experts to do the analysis?