STANDARDS RESEARCH

Towards a Guideline for Assessing Climate Change Vulnerabilities of Northern Airports

August 2020

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Acknowledgements

Funding for this project was provided by Transport Canada.

Table of Contents

Executive Summary

Transportation infrastructure in the North connects communities and fosters security to a degree that is unparalleled in other regions in Canada. Economic and lifestyle factors in this region rely heavily on the transportation network – a network that, when reliable, reduces the costs of living, supports inter-community and social mobility, and promotes effective resource development. One hundred and fifty-six airports, of which 67 are located in the Yukon, Northwest Territories, and Nunavut, lie within the permafrost zones of Canada. Of those airports, 32% can be found in the continuous permafrost region and an additional 45% in regions with discontinuous permafrost. Air temperature in northern Canada has warmed and is projected to continue to do so at more than double the global rate, significantly impacting permafrost, as well as local weather conditions that are critical for safe aviation operations.

Recognizing the critical nature of airport infrastructure, a literature review and a stakeholder questionnaire were conducted with the goal of compiling existing analysis methodologies for carrying out risk and vulnerability assessments for northern aviation infrastructure in a changing climate. The review and the questionnaire revealed that risk and vulnerability assessments have been completed to date; however, inconsistencies were identified regarding the methodology and associated definitions, including the approach for climate change data inclusion, addressing the uncertainties in the climate change projections, and the physical and operational elements considered. As a result, it is recommended that a specific standard on climate change vulnerability assessments for northern airports be developed that includes guidance on the following:

- The methodology to be used for the analysis;
- Risk and vulnerability assessment terminology;
- Climate parameters and their projected changes;
- Consideration of uncertainties from the projections and operations (e.g., traffic volumes, aircraft types); and
- How to apply the results in a decision-making process as well as in operations and maintenance.

A climate change vulnerability assessment should address the full spectrum of airport operations and maintenance activities and not be limited to the assessment of the physical infrastructure. This broader, holistic view ensures that the current and future demands of an airport are met, its resilience identified, and adequate adaptation measures presented. In particular in the North, planning is essential as significant effort may be required to implement particular measures.

Based on the work completed, the need for a standard in support of climate change risk and vulnerability assessments was identified. This standard should be specifically tailored towards northern airport infrastructure and include the holistic view required for adequate adaptation planning.

"Northern transportation infrastructures are critical in the absence of any all-season road network and will likely be utilized even more in the future, with increasing populations and desire to connect to the South."

1.0 Introduction

1.1 Northern Airport Context and Importance

Northern transportation infrastructure "connects communities and fosters security like no other place in Canada" [1]. Thus, the economy and way of life in the region relies heavily on the transportation network [2]. Reliability in this network "reduces the costs of living, supports inter-community and social mobility ... [and] fosters effective resource development" [2].

Most northern communities are isolated with air travel being their only year-round option for the transport of goods and people [2]. Of the airports present in the Territories and Nunavik (northern Quebec), the majority are founded on permafrost [2]–[4] with gravel traffic surfaces (Section 0). The permafrost foundation is sensitive to changes in climate conditions, particularly warming air temperatures and precipitation affecting the dangers to which the infrastructure is exposed. Pendakur [3] noted dangers,[1] including permafrost degradation (also noted in [5], [6]), changing or increasing snow drifting patterns, rainfall, surface icing, wind, and fog, all of which impact aviation safety, airport operations and maintenance, and runway and taxiway stability.

As indicated, these infrastructures are critical in the North and, in the absence of any all-season road network, will likely be utilized even more in the future; with increasing populations [7], [9] and desire to connect to the South, combined with decreasing durations of the winter road season [3].

The critical nature of these infrastructures has not influenced decision-makers to support and address the challenges associated with the current state of the infrastructure nor potential resilience to climate change. Northern aviation infrastructure is "too much of an afterthought" when it comes to infrastructure decisions [1]. For example, the Auditor General of Canada (AGC) [10] reviewed whether Transport Canada (TC) addressed and assessed civil aviation infrastructure needs in Canada's North. The AGC concluded that TC had all the information needed to address challenges for northern Canada's aviation infrastructure but did not take the lead to meet these challenges. In addition, the AGC determined that more investment is needed to address the safety disparity [10].

The purpose of this study is to develop a comprehensive set of best practices and guidance material for users and regulators, on the critical steps that must be taken when conducting a climate change risk/vulnerability assessment for airports located in Canada's North. The study included a review of the climate and vulnerability/risk assessment literature and a questionnaire and interviews with stakeholders to determine existing methods in use to analyze airport, transportation, and other infrastructures with case study examples.

[1] An event or condition that causes damage to infrastructure or safe conditions.

Information on the use of climate data models to support the assessment and recommendations for the development of effective adaptation strategies for risk reduction are also presented.

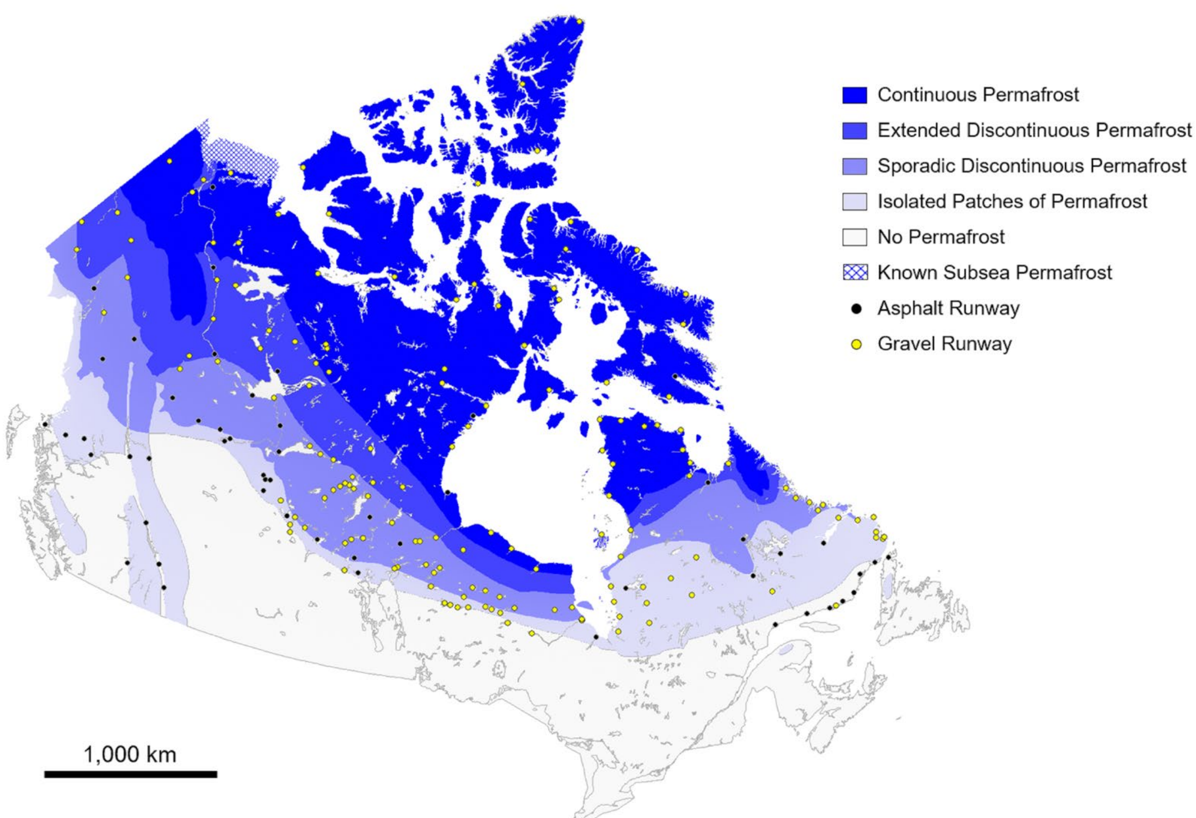
1.2 The North

In this report, "the North" or "northern" is used in the context of where the environment is controlled by extended periods of freezing temperatures and associated terrain conditions. Politically, northern Canada, or "the North," consists of the 3.5 m km^2 of the three territories – Yukon, Northwest Territories, and Nunavut. In this report, however, we focus on challenges typically related to changes in permafrost[2] conditions and therefore extend the traditional definition of the North to areas where permafrost may be present. In particular in eastern Canada, this includes northern Ontario, Manitoba, and Nunavik. As such, the term northern or the North, is used in a broader context within this report than it would traditionally be used.

1.3 An Overview of Airports in Canada's North

A total of 202 airports [12] located in seven provinces and the three territories, which are located within or close to a permafrost zone, were evaluated in terms of their spatial distribution in comparison to the 1995 permafrost map of Canada from the National Atlas of Canada [13] (Figure 1). A total of 156 airports, of which 67 are located in the three Canadian territories, lay within a permafrost zone. Of those, about 32% are

Figure 1: *Distribution of 202 airports in or close to a permafrost zone. Airport information is based on Canadian Airport Charts [12], and the permafrost distribution map is based on The National Atlas of Canada [13]*



[2] Soil or rock, with or without ice that have been at or below 0°C for a minimum of two consecutive years [11].

Table 1: *Permafrost Distribution and Runway Characteristics of Airports Located in Permafrost Zones. All Runway Data from Canadian Airport Charts [12]*

	Runway Characteristics (length / surface)									
	< 600 m < 2000 ft		600 m – 1200 m 2000 ft – 4000 ft		1200 m – 1800 m 4000 ft – 6000 ft		1800 m – 2400 m 6000 ft – 8000 ft		> 2400 m > 8000 ft	
	grav.	asph.	grav.	asph.	grav.	asph.	grav.	asph.	grav.	asph.
Continuous Permafrost	1	0	19	0	21	0	5	2	0	2
Extensive Discontinuous Permafrost	0	0	12	0	6	1	0	2	0	0
Sporadic Discontinuous Permafrost	1	0	23	0	11	9	0	3	0	1
Isolated Patches of Permafrost	0	0	18	0	5	6	0	7	0	1
TOTAL	**2**	**0**	**72**	**0**	**43**	**16**	**5**	**14**	**0**	**4**
	1%	—	46%	—	28%	10%	3%	9%	—	3%

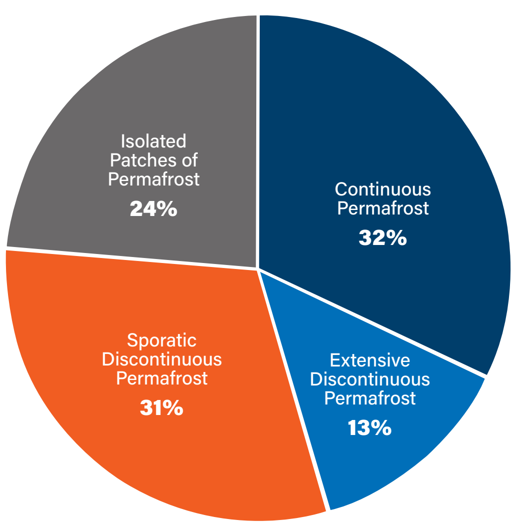
NOTES: *For airports with more than one runway, the characteristics of the longest runway were included. Runway surface:* ***asph.****: asphalt;* ***grav.:*** *gravel.*

Table 2: *Territorial and Provincial Distribution of Airports Located in Permafrost Zones*

	YT	NT	NU	BC	AB	SK	MB	ON	QC	NL
	9	24	28	6	9	15	16	10	26	13
Zones*	1, 2, 3	1, 2, 3, 4	1, 2	3, 4	3, 4	2, 3, 4	1, 2, 3, 4	1, 3, 4	1, 2, 3, 4	3, 4

*** Permafrost Zones** *(bold marks the dominant zone):* ***1*** *Continuous Permafrost;* ***2*** *Extensive Discontinuous Permafrost;* ***3*** *Sporadic Discontinuous Permafrost;* ***4*** *Isolated Patches of Permafrost*

Figure 2: *Distribution of Canadian airports located within a permafrost zone*



located in the continuous permafrost zone, 45% in discontinuous permafrost zones, and the remainder in the zone of isolated patches (Figure 2). Table 1 provides additional information specifically with regards to runway characteristics. This compilation, as well as Figure 1, highlights that most northern airports have gravel runways and have runway lengths between 600 m and 1200 m (2000 ft and 4000 ft). There are total of four asphalt runways in the continuous permafrost zone (Churchill, MB; Inuvik (Mike Zubko), NWT; Iqaluit, NU; Rankin Inlet, NU) and 16 are in the two discontinuous zones. Finally, Table 2 provides a provincial and territorial distribution of the airports shown.

1.4 Northern Airport Requirements

Airports in the North differ from airports in the South in many ways. The harsh climatic conditions affect structural components and operations in various complex manners. The changes in the climatic conditions manifest themselves through changes in weather patterns, such as major changes in wind direction, freeze-thaw cycles, or moisture and fog development. These changes can have impacts on infrastructure foundations in response to thaw settlement or erosion, or in terms of airport operations. A need has been identified for improvement and investment in northern aviation infrastructure, to meet current safety standards and to adapt to climate change. In response to this need, various organizations have provided comments for addressing climate impact and resiliency in the northern infrastructure:

- Strategies for northern Canada are not complete without climate change adaptation and that is not complete without a focus on infrastructure [1].
- New codes and standards are needed to reflect "what it takes to design, build, and maintain infrastructure in the North" currently and including climate change [1].
- Northern airports should maintain the highest possible standard to support the largely roadless communities [14].
- Infrastructure adaptation plans should include evaluation of potential risks, damage, and costs of permafrost degradation to critical infrastructure [15].
- Risks can be mitigated "with careful planning and investment," as long as "climate-related risk assessments and vulnerability analyses are incorporated into maintenance, upgrading, and lifecycle management programs" but recent research shows this is not routinely happening [16].
- Risk assessment methods are recommended to address the uncertainties from climate change that are and will continue to affect these infrastructures [17].

Several standards have been developed to address infrastructure design, maintenance, and changing climate conditions. These include:

- CSA Group. (2019). *CSA PLUS 4011:19 – Technical Guide: Infrastructure in permafrost: A guideline for climate change adaptation.*
- CSA Group. (2019). CSA PLUS 4011.1:19 – *Technical Guide: Design and construction considerations for foundations in permafrost regions.*
- CSA Group. (2019). CAN/CSA S16:19 – *Design of steel structures.*
- CSA Group. (2015). CAN/CSA-S503-15 – *Community drainage system planning, design, and maintenance in northern communities.*
- CSA Group. (2014). CAN/CSA-S500-14 – *Thermosyphon foundations for buildings in permafrost regions.*
- CSA Group. (2014). CAN/CSA-S501-14 – *Moderating the effects of permafrost degradation on existing building foundations.*
- CSA Group. (2014). CAN/CSA-S502-14 – *Managing changing snow load risks for buildings in Canada's North.*
- BNQ. (2017). CAN/BNQ 2501-500/2017 – *Geotechnical Site Investigations for Building Foundations in Permafrost Zones.*

However, no existing standard covers the specific needs of northern airport infrastructure nor includes the climatic conditions which, if they change, may greatly impact the operations and maintenance of the airports.

2.0 Literature Review

The literature review was designed to focus on three areas of interest:

- The existing and projected climate conditions in Canada's North;
- Methods and examples of risk assessment methodologies outlined in policy and case study documents; and
- Recommended types of adaptation strategies.

2.1 Climate Change

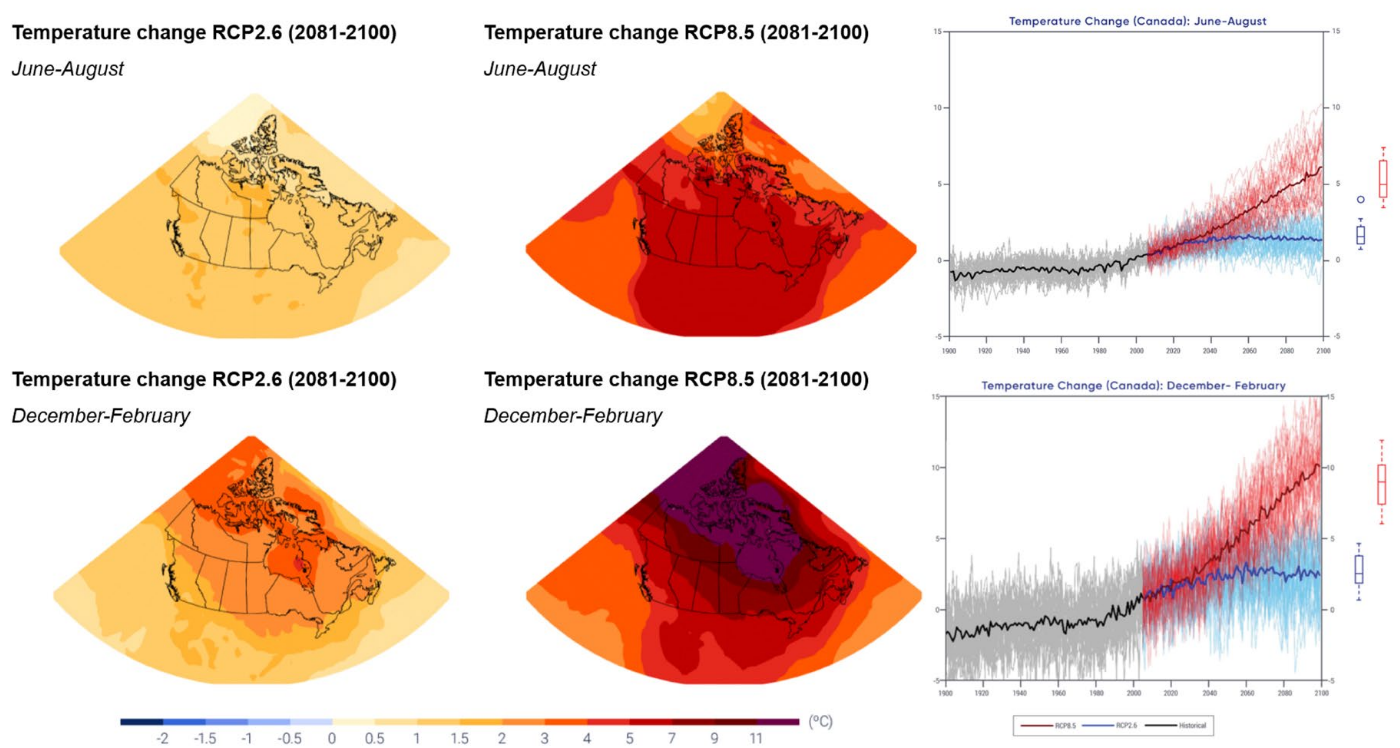
2.1.1 Arctic Region

Climate change leads to changing frequency, intensity, spatial extent, duration, and timing of extreme weather and climate [18]. In the Arctic, average air temperatures have and are projected to increase more than twice as fast as the rest of the world [5], [19], [20]. The annual duration of snow cover in the Arctic is decreasing by two to four days per decade, even with an increasing accumulation of snow [21]. These and other factors have increased active layer thicknesses of the permafrost, resulting in a delay in the date of active layer freeze up in northern Alaska by two months and have changed vegetation types, which in turn alters snow-drifting patterns [21].

Global climate models (GCMs) have projected additional warming for the Arctic [22]. Representative concentration pathways (RCPs) 4.5 and 8.5 have projected mean annual air temperatures of 0.6°C and 3.3°C by the 2080s for the Canadian Arctic, respectively; these temperatures are 6.5°C and 9.2°C warmer than current climate norms [23]. More importantly for permafrost regions, warming is non-uniform throughout the year. Summer temperatures are increasing but at a smaller rate than winter temperatures [21], as presented in Table 3: and Figure 3:. Warming winter temperatures impact permafrost due to the reduction in the quantity of heat extracted during the winter through the ground surface or via passive cooling [24], [25]. Airport infrastructure is particularly vulnerable to changes in temperature. The albedo and thermal properties of the infrastructure materials, among other factors, lead to warmer surface temperatures and greater active layer depths on operational surfaces. Consequently, this heat must be extracted during the winter to keep the underlying permafrost from degrading.

The projected global sea level rise by 2100 is approximately 0.52 m to 0.74 m for RCP 4.5 and 8.5, respectively [21]. Bush and Lemmen [20] concluded that local sea level is projected to rise along most of the Atlantic and Pacific coasts of Canada and the Beaufort coast in the Arctic where the land is subsiding or slowly uplifting due to post-glacial rebound. Where the land is uplifting fastest (e.g., in Hudson Bay), local sea level is projected to fall. In those areas where local sea level is projected to rise, the frequency and magnitude of extreme high-water level events will increase. The loss of sea ice in the Arctic and Atlantic Canada further

Figure 3: *Projected changes in air temperature increases in Canada for 2081 to 2100 by summer and winter seasons and RCP [20]*



increases the risk of damage to coastal infrastructure and the ecosystem as a result of larger storm surges and waves. A significant number of airports in Canada's North (approximately 30) are at elevations of less than 50 m [12] and are therefore more vulnerable to these projected changes in sea level and ice cover.

Table 3: *Projected Arctic Air Temperature Increases for the 2080s by Summer and Winter Seasons and RCP [21]*

	Summer (Jun-Aug)	Winter (Dec-Feb)
RCP 4.5	3–4°C	7–9°C
RCP 8.5	4–7°C	11–13°C

Most GCMs provide results in a larger grid that is useful for regional or local conditions [26]. To downscale these data to useful and practical scales, statistical methods are used which introduce additional assumptions and bias corrections.

2.1.2 Canadian North

Climate change is evident in Canada [1], [20]. The North has experienced some of the most significant warming on the planet with average air temperatures warming 1.6°C to 2.6°C between 1948 and 2014; the largest change has occurred in the Mackenzie Valley area [3]. Measured permafrost temperatures are increasing and warming up to 3°C has been observed in the uppermost 10 m from the ground surface since 1970 [27]–[29].

In some regions, existing downscaled[3] air temperature data are available from governmental or university climate centres or organizations. A list of resources for these data in Canada are presented in CSA PLUS 4011:19 and CSA Plus 4011.1:19 [27], [28].

2.1.3 Climate Data Uncertainty

There are limits to climate scientists' ability to project future climate conditions due to the imperfect representation of climate complexity and foresight of human behaviour [26]. These uncertainties are aleatory[4] for the natural variation of the climate, and epistemic[5] for the model response, or sensitivity to forcing, and projection of future emissions and climate drivers [26]. Intergovernmental Panel on Climate Change reports (e.g., [19]) include a level of confidence in the presented data that show the robustness of the evidence to include the epistemic uncertainty in the model results.

Statistical methods can also be used to create climatic distributions of weather from multiple models or by the perturbed physics ensemble (PPE) [26]. The multiple model method uses an ensemble of GCMs to create a distribution of climate results, but it underestimates the real extent of the climate distributions and should be considered as a lower bound. The PPE method varies input values within a single GCM and uses the outputs, with a credibility rating applied using the Bayesian framework, to develop distributions. However, the PPE method is best utilized for probabilities between 10 and 90% and not the tails of the distributions which are of greatest interest when designing for extreme weather events.

2.1.4 Climate Data for Infrastructure Design

Climate change will impact infrastructure throughout its service life, but the amount and rate of change is uncertain and must be included in infrastructure design or redesign [23], [26]. Most often, climate and extreme weather probabilities used as the basis of engineering design are written into codes and standards assuming that the average shifts but the distributions of climate data remain unchanged. However, this assumption of stationarity may not be valid for future climate projections [26], [30].

The organizations or methods outlined in the previous section could provide some of those data, but it may be necessary to consult the expertise of a climate scientist or other climate projection specialist depending on the project requirements [26], [31]. However, some of the weather events and climate conditions that affect airport

[3] The process of taking data from a larger area and using local factors to scale the data to a smaller aerial extent.

[4] Uncertainty or variability due to inherent randomness of a parameter or variable.

[5] Uncertainty due to imperfect knowledge of a randomness of a parameter or variable; bias between calculated statistics and reality.

"Climate change will impact infrastructure throughout its service life, but the amount and rate of change is uncertain and must be included in infrastructure design or redesign."

infrastructure and operations do not have projections available for future conditions, such as wind direction or intensity changes, freeze-thaw cycles, and visibility. Dangers associated with these parameters will have significant uncertainties and limitations.

3.0 Risk Analysis Methods

Risk and vulnerability assessments to deal with climate uncertainties are recommended by multiple engineering organizations [32]–[34] and the International Organization for Standardization (ISO 31000).

The process of completing a risk analysis includes the following steps, as adapted from the Public Infrastructure Engineering Vulnerability Committee (PIEVC) [35][6] and Public Safety Canada [36]:

1. Identify the dangers to which the infrastructure is exposed;
2. Characterize these dangers;
3. Calculate or assign the hazard, vulnerability, and consequence;
4. Evaluate the risk by multiplying the hazard by vulnerability and consequence;
5. Rank the risks;
6. Treat those that exceed the infrastructure or the stakeholder's risk tolerance; and
7. Monitor performance and reassess the risks periodically.

This section outlines methods of varying complexities that are used to analyze infrastructure with these basic steps. In general, there are three possible levels of risk analysis [36] ranging from qualitative analysis to fully quantitative analyses. In a Tier 1 analysis, data from published sources are used with predefined rubrics to complete a qualitative analysis. In a Tier 3 assessment, all of the risk analysis factors are calculated from the most up-to-date data and methods available at the time of the analysis. The combination of quantitative methods and qualitative methods where there are gaps in the data, along with engineering judgement, defines a Tier 2 analysis.

3.1 Definitions and Terminology

The domain of risk assessment does not use terminology consistently. For clarity in this report, the following definitions from Lacasse *et al.* [38] are used:

Danger: Phenomenon that could lead to damage to a system, described by geometry, mechanical and other characteristics.

[6] Effective March 30, 2020, ownership and control of the PIEVC Program, including the Protocol, has been transferred to a partnership consisting of the Institute for Catastrophic Loss Reduction (ICLR), the Climate Risk Institute (CRI), and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

Exposure: Circumstances of being exposed to a danger.

Hazard: Probability that a danger occurs within a given period of time.

Consequence: The worth of a loss, direct or indirect, from the occurrence of a danger.

Vulnerability: The degree of loss to a given element or set of elements within the area affected by a hazard, expressed on a scale of 0 (no loss) to 1 (total loss).

Risk: Measure of the probability and severity of an adverse effect to life, health, property, or environment. Risk is hazard multiplied by consequence and vulnerability.

For a climate change risk assessment, the danger is an impact as a result of climate change over a specific timeframe, but for this danger to occur, the system must be exposed to the climate condition that will initiate the danger's occurrence.

Other relevant definitions used in this report:

System: The location, infrastructure, interaction or element under analysis.

Fragility: A measure of changes to exposure, hazard, consequence, vulnerability or risk in light of an uncertain condition.

Resilience: The capacity of a system, community or society to absorb, accommodate and recover from climate change impacts and maintain function through the changes.

Mitigation: Actions that will reduce the concentration of greenhouse gases within the atmosphere that drive climate change.

Adaptation: Actions that will reduce the exposure, hazard or consequence associated with danger to a system; actions that improve a system's resiliency.

Stakeholder: Persons or groups with vested interests in a system. This could be community groups, governmental organizations, cultural groups, managing organizations, environmental groups, researchers, etc.

3.2 Risk Analysis Process

3.2.1. Identify (1) and Characterize Dangers (2)

The first two steps in the analysis identify and characterize dangers. For dangers associated with changing climate conditions, exposure is a key item in risk assessment [18]. Exposure can be determined in two ways: (1) top-down or (2) bottom-up [26], [39]. In a top-down approach, projected climate conditions are used to determine the climate event induced dangers to which the infrastructure is exposed. Bottom-up approaches begin with the infrastructure to determine climate-event-induced dangers that have the potential to adversely impact the infrastructure; the climate projections are then used to determine the infrastructure's exposure.

The two approaches are illustrated below for an example runway founded on permafrost where one section of the runway is founded on bedrock and another on ice-rich soils:

- **Top-down:** Average air temperatures are projected to increase and will result in permafrost degradation across the infrastructure. Only the portion of the runway founded on ice-rich permafrost will be exposed to thaw settlement as a danger.
- **Bottom-up:** The site's ice-rich permafrost poses a danger if the permafrost degrades due to the potential for thaw settlement. At the site, average air temperatures are expected to increase, exposing that section of the runway to thaw settlement dangers.

Once the dangers have been identified, they must be characterized. For a qualitative analysis, this characterization can be a verbal description of the danger [24]. For example, changing patterns of snow accumulation and drifting due to shifting wind patterns will alter the locations of, and increase feedback for, permafrost degradation at the toe of embankments, initiating embankment slope instabilities. In a quantitative analysis of hazard, the danger is defined mathematically from a limit state function (factor of safety equation) or serviceability limit. Using this example of snow drifting, the danger would be the slope stability factor of the safety equation combined with a thermal analysis for the given climate condition.

3.2.2. Calculate or Assign Hazard, Consequence, and Vulnerability (3)

The third step in the analysis forms the majority of the effort associated with a risk assessment. Depending on the level of effort identified, the hazard, consequence, and vulnerability can be calculated or assigned.

Hazard: Hazard can be assigned from a rubric defining probabilities of occurrence using descriptions, like those used in Table 4, or can be directly calculated. When using a rubric, judgement is required in assigning the hazard factors. Hazard can be calculated for a danger using past occurrence data or from the uncertainty in input parameters; further discussion is presented in Brooks [24]. In the context of climate-change-related dangers, past experience cannot be used to determine hazard as the changing climate variability will not be reflected in historical data. There are additional challenges and complications for hazard calculation from input parameter uncertainties; specifically, sufficient data are required to determine distribution functions for all uncertain parameters, including projected climate variation and interannual variability.

Table 4: *Example of a Hazard Rubric Adapted from Engineers Canada [35]*

Hazard Factor	Climate Event Hazard		
0	negligible	< 0.1 %	negligible
1	improbable	5%	1:1,000,000
2	remote	20%	1:100,000
3	occasional	35%	1:10,000
4	possible	50%	1:1,000
5	often	65%	1:100
6	probable	80%	1:10
7	certain	> 90%	1:1

Note: *The % is the probability of occurrence of a danger, while the ratio is the frequency of occurrence in years.*

Consequence and Vulnerability: As with hazard, consequence can be calculated or can be assigned a factor from a rubric based on fatalities, cost of repair, or other factors (e.g., environmental, social, or cultural impacts). Consequence factors, defined from a rubric, can be developed in consultation with project stakeholders. Calculated consequence can be the direct costs (i.e., repair costs of the infrastructure) or combined with the indirect costs (i.e., economic losses, costs of transport via another mode, or fatalities and environmental impact costs) in a quantitative or semi-quantitative analysis [24], [40].

Vulnerability and consequence are often linked and are not considered independent unless the consequence of a specific danger is difficult to calculate specifically; for example, the consequences of a tsunami inundation for a community. In this case, the consequence is defined as the cost of total loss of the infrastructure in the exposed area and vulnerability is a factor reflecting and correlating the severity of the danger (i.e., tsunami wave height) and damage [40]. Vulnerability is a key term in distinguishing high probability/low consequence dangers from low probability/high consequence dangers [41].

3.2.2.1 Case Studies for Hazard, Consequence and Vulnerability

Practical examples of risk assessments, their methods for hazard, consequence, and vulnerability determination are presented below, classified according to the level of effort and data required to complete the analysis.

Qualitative methods (Tier 1) use different approaches:

- ICF [41] created a climate risk framework for British Columbia using defined stakeholder meetings to assign hazard and consequence factors from rubrics for a qualitative analysis that took into account multiple consequence sectors, including health, social function, cultural resources, economic vitality, and natural resources. The method was similar to Tonmoy *et al.* [37]. Vulnerability is considered in the potential consequences directly.
- A qualitative vulnerability assessment of the North Alaska Highway was completed using a method developed using site permafrost conditions [43]. The vulnerability analysis was based on a combined measure of volumetric ice content, thickness of the permafrost, and permafrost temperatures. Hazard and consequence were not considered in this analysis.

- Researchers from the University of Alaska Fairbanks (UAF), the US Army Corps of Engineers (USACE), and the Cold Regions Research and Engineering Laboratory (CRREL) [44] worked in conjunction to develop a qualitative analysis method which combined consequence (impact factor) with hazard (time to damage, probability based on frequency) with a confidence factor. The result is a qualitative analysis of various Alaska communities and their risk rank for erosion, flooding, and permafrost thaw settlement.

Semi-quantitative methods (Tier 2) use the data available to calculate a portion of the hazard, consequence, or vulnerability metrics used in a risk analysis:

- The PIEVC's method has allowances for each of the tiers in the analysis. This analysis method pairs an infrastructure element with a climate change event. The hazard and severity associated with each pairing is calculated or assigned a value from rubrics, where severity is defined as the consequences of loss in performance of functionality. This method has been used in the analysis of climate risk for three northern airports (Inuvik, NT; Cambridge Bay, NU; Churchill, MB) [45]–[47] and 100 km of Highway 3 near Yellowknife, NT [48]. The airport studies are discussed in greater detail in Section 4.0.
- A semi-quantitative method for risk assessment was developed by Brooks [24]. This method was bottom-up and used Monte Carlo statistical methods and engineering calculations to quantitatively determine the hazard associated with a site and its climatic distribution. The method is specific to permafrost embankment infrastructure and dangers affecting that infrastructure type. Climate change is accounted for in the method, using a fragility assessment, where climate parameters are varied, and the hazard and risk recalculated.

A full **quantitative analysis** (Tier 3) of risk in a northern context has not been completed to the authors' knowledge. The authors suspect this is due either to a lack of data or significant uncertainty within the analysis.

3.2.4 Evaluate (4) and Rank Risks (5)

Steps 4 and 5 involve evaluating the risk value for each danger, which is completed by multiplying hazard, consequence, and vulnerability. Once the risk is calculated, risks are ranked from highest to lowest.

3.2.5 Determine Risks Exceeding Tolerable Threshold (6)

In step 6, working with stakeholders is considered necessary to determine a risk threshold at which the infrastructure must be adapted to increase its resiliency. The decision to accept a level of risk will require a balancing of risks, costs, benefits, and other social values to determine an acceptable threshold [26], [49], [50]. Decision-making analysis methods and strategies for adaptation are discussed below in further detail.

A review of the thaw settlement vulnerability study [43] of the North Alaska Highway in the Yukon was completed to identify locations to test adaptation methods for the highway to increase its resiliency in relation to climate change. Each site was assessed individually, and the specific adaptation methods recommended were based on site conditions and future climate projections.

3.2.6 Monitor Performance, Reassess, and Communicate (7)

Step 7 takes place once a risk assessment is completed. At that stage, the climate factors and indicators of the riskiest dangers' occurrence identified should be monitored and reassessed periodically [51]. The level of risk accepted should be communicated to stakeholders and this should include a discussion of climate projection uncertainty and how that uncertainty affects or limits the risk assessment [26], [52].

3.3 Fragility Analysis

Fragility analysis is a method where an uncertain parameter, often climate-specific, is systematically varied to recalculate or reassign hazard, vulnerability, and consequence values. A correlation between the parameter's variation and risk, hazard or consequence can then be established. This method was proposed by Brooks [23] to correlate hazards for permafrost embankment infrastructure to mean annual air temperature, assuming stationarity of the air temperature distribution.

3.4 Infrastructure Resiliency

Infrastructure resilience is a complex problem involving the physical infrastructure, people, the environment, operations, maintenance, and emergency response [50]. In essence, it requires an intersystem analysis approach to include power, healthcare, distribution, communications, etc. To increase the development of a more resilient infrastructure, a number of disciplines must collaborate, including policymakers, planners, investors, industry representatives, designers, engineers, researchers, disaster response professionals, standard developers, and community members [53].

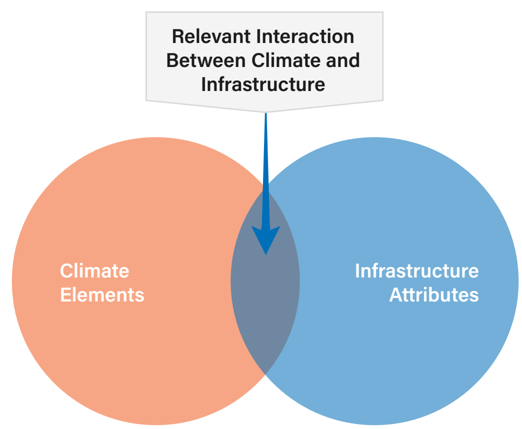
"If communities can make their infrastructure resilient to the impacts of climate change, they can increase the likelihood of rapid recovery" [53]. Any increase in infrastructure resiliency cannot be completed without identifying vulnerabilities by completing a risk assessment [52]. "The key to developing cost-effective adaptation of climate change risks is a combination of early action, on-going infrastructure and operation improvements, and no-regret measures" [52].

4.0 Existing Airport PIEVC Analyses

PIEVC methodology pairs infrastructure components and climate events, for which a relevant interaction exists (Figure 4), which are each analyzed individually depending on the type of infrastructure and its potential climate change factors. The iterations may result in a large number of infrastructure components, known as climate parameter pairs. The reporting includes confidence in the potential for the climate parameters to occur, but it is not included in the risk calculation. The airport assessments included climate effects on airport operations, including visibility, low-cloud ceilings, and frost; however, it is difficult to project the probability of occurrence for these events as they are "second or third order climate events" that are not easily projected from GCMs [45]–[47].

In the three airport studies available for northern airports in Canada – Cambridge Bay, Nunavut [45], Churchill, Manitoba [46], and the Mike Zubko Airport in Inuvik, Northwest Territories [47] – the major climate parameters that are projected to impact future airport operations are rainfall, visibility, frost, ground thawing, and climate variability. The highest risk combinations were ranked as medium-high and these tended to be operations and maintenance related. No engineering actions were recommended in these assessments; however, there were recommended actions to improve data availability for future assessments. These actions consisted of documentation of maintenance and repair data, systematic collection of frost, visibility and weather conditions, review of management procedures, and creating an asset management protocol.

Figure 4: *PIEVC: Climate and infrastructure interaction. Adapted from PIEVC [35], with permission from the Institute for Catastrophic Loss Prevention*



5.0 Adaptation Strategies

A hierarchy of adaptation options has been proposed in the literature to build infrastructure resilience and reduce risks associated with climate change [30], [51], [54] that comprise no-regret actions, low-regret actions, and adaptive management or learning.

- **No-regret actions** are those actions that would be taken without climate change but increase resiliency or adaptive capacity in light of it. These include monitoring, data gathering, forensic studies of past disasters, and disaster planning.

- **Low-regret actions** includes options such as the observational method (described in further detail in the next section), regulation or avoidance of development in locations vulnerable to climate change, adaptive maintenance strategies, test plots of adaptation measures, strategic planning incorporating climate change, and retrofitting to increase resilience. The actions tend to be less expensive, relative to the total project costs and either explore or test future adaptation methods or incorporate climate change planning in all infrastructure areas (i.e., operations, safety, asset management, etc.).
- **Adaptive management** includes reconstruction or replacement of infrastructure, or infrastructure relocation from highly vulnerable locations. These actions tend to be high cost and decision-making tools that can or should be used to select options of the greatest benefit.

6.0 Other Analysis Methods

In situations of deep uncertainty, like those associated with climate change, "the decision-making process becomes as important as the facts that support the decisions" [50]. The following additional methods may be applied for decision-making following the completion of a risk assessment.

- **Cost-benefit or cost-effectiveness analysis:** Used to differentiate between alternative plans on the basis of present cost over a period of time, usually annually or through the service life of the infrastructure. Analyses must consider uncertainties in climate conditions, but this is difficult to include [31], [54].
- **Multi-criterial decision analysis:** Costs and benefits are measured on a values scale reflecting the desirability of the options from the decision-maker's perspective [31].
- **Robust decision-making:** Identify the full range of plausible future states, the robust alternative is the option that covers as many future states as possible. Often used for situations with high uncertainty [31].
- **Observational method:** Design or select the alternative that best covers the most probable, not most unfavourable, conditions with provisions to augment the design during the service life based on monitoring [26].
- **Participatory methods:** Methods that support the inclusion of experts and users in the decision-making and assessment process; best results are accomplished with a wide variety of stakeholders [31].

7.0 Knowledge Gaps and Reported Recommendations for Northern Aviation Infrastructure

Climate change is affecting and will continue to affect Canada. The rate and magnitude of change is amplified in the Arctic. Unfortunately, the Arctic, which is "most susceptible to the adverse impacts of climate change, is most reliant on transportation infrastructure" [55], particularly aviation.

Northern aviation infrastructure is often founded upon permafrost (Section 0) which may be ice-rich and, generally, consists of a gravel runway with ancillary taxiways and structures. The presence of permafrost and the critical nature of aviation infrastructure to northern communities make the climate change risk assessments key tools in planning and decision-making for adaptation. Climate risks cannot be reduced without careful planning and investment, but recent research shows integration of risk and vulnerability analyses into maintenance, upgrading, and life-cycle management programs is not happening on a routine basis [16].

Based on the literature review that was completed to determine existing methods for risk assessments with attention to the remote northern aviation infrastructure, various methods and a generalized risk analysis process were identified. However, these methods have inadequacies for northern infrastructure. The following gaps were identified through the literature review:

1. For accurate decision-making, consistent methodologies for the development of local climate change projections via downscaling across climate centres should be used [56]. This will allow comparison of risk assessments across territories and provinces.
2. The risk assessment methodologies have been adapted for various levels of effort depending on the resources and data available to complete the analysis. However, no method is consistent with its definitions, methodology for climate change data inclusion, or

"Transport operations are more sensitive to climate change than transport infrastructure"

handling of climate change projection uncertainty. To that end, risk assessors should work in consultation with climate scientists for an interdisciplinary understanding of climate uncertainty and consistent handling of the data.

3. "Transport operations are more sensitive to climate change than transport infrastructure" [57]. Existing risk assessment methods focus on the state-of-infrastructure and do not include provisions for maintenance and operations. On a day-to-day basis, it is maintenance and operations that directly interact with the consequences of climate change.

4. Once a risk assessment has been completed, little action is taken for adaptation. A lack of action could be due to the following reasons: (1) a lack of publications reporting the adaptation; (2) a lack of understanding of the risk assessment's results and interpretation; (3) a lack of funding available for action; (4) uncertainty or a lack of confidence in new methods for climate change adaptation; (5) or a "lack of awareness, information, and guidance," which were identified as "key barriers preventing aviation organizations from taking climate adaptation" measures [52]. New methods for adaptation should be tested at large or full scales to prove their effectiveness and be designed specifically for the site's conditions [21].

5. None of the risk assessment case studies are known to have been repeated in order to determine risk changes with time and additional climate change. Their effectiveness in identifying the greatest risks has not been tested. Empirical correlations between risk and previously observed danger occurrence has been completed [24], but risk (including consequence, vulnerability, and resilience) has not been analyzed over the life of an infrastructure.

While methods for risk assessment exist, additional work needs to be completed to improve and prove their effectiveness and use in planning and adaptation of northern infrastructure.

8.0 Questionnaire and Interviews

8.1 Questionnaire Introduction

A stakeholder questionnaire was developed in order to collect information regarding current practice and need for risk assessments of northern airports. The literature review presented in the previous section was used as a starting point to design a questionnaire that was split into the following seven main sections:

- General information about the respondents;
- General information about the airports with which they interact;
- The consideration of climate change in their analyses, planning, etc.;
- Risk and vulnerability assessment methodologies;
- The inclusion of climate change in risk and vulnerability assessments;

- Result communication and usefulness, follow up analysis; and
- Respondents' thoughts on a new standard.

In total, 100 individuals were contacted, including managers, researchers, designers, and regulators. The questionnaire was completed within Microsoft Forms and a link to the questionnaire was distributed to those contacted and to professional networks whose members might be interested in the topic. The questionnaire was opened to respondents on February 17, 2020 and closed on March 13, 2020.

A total of 27 respondents participated in the questionnaire. A summary of the key results is presented in the following section. The complete responses are presented graphically, in word clouds and in text form.

8.2 Results

8.2.1 Respondent Information

The respondents were employed by federal, provincial, or state departments of transportation, worked with engineering consulting companies, or worked in universities (Figure 5) and who worked routinely with embankment supported infrastructure (i.e., airports and roadways). The aspect of the respondents' work with northern airports varied but included persons involved in planning, operations or maintenance, infrastructure design, and users (Figure 6).

Figure 5: *Respondents' organization type*

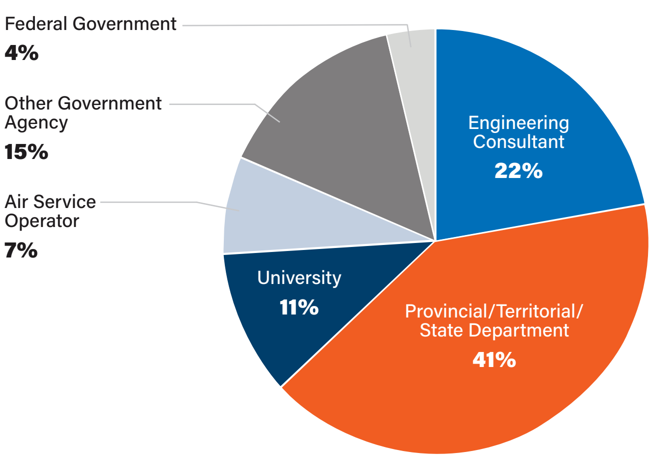
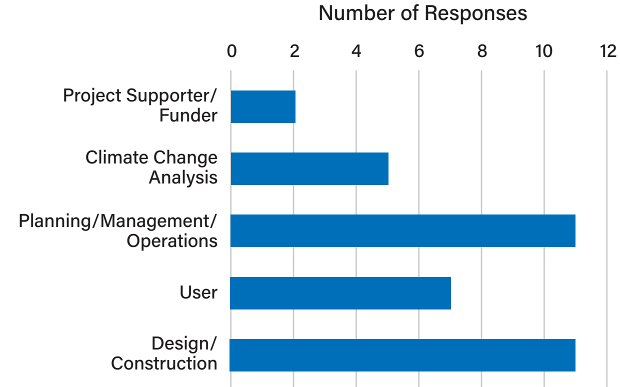


Figure 6: *Respondents' interaction with northern airport infrastructure*



Note: *These general categories were derived from long-form text responses and respondents may fall into multiple categories.*

8.2.2 Infrastructure Types and Existing Conditions

The respondents were asked to respond to the following questions either thinking of the airport they interacted with most or an average of the majority of the airports they interacted with.

In general, the existing northern airport infrastructure met their needs, their organizations' needs, and those of the communities the airports serve. The importance of these airport infrastructure systems also came to light in the responses: 30% of respondents noted the airport they interacted with most often was the sole connection for the community it serves, and an additional 37% noted that they interacted with multiple airports and some of those were the communities' sole connection. The airports were located within 20 km (80%) of the community, with the majority (55%) of airports located within 5 km. More than 90% of the respondents noted the airports were located in permafrost zones and that 44% were underlain by ice-rich permafrost. Approximately 50% of the airports did not have a paved runway. The condition of the infrastructure was reportedly moderate, but 60% (25 respondents) noted that they had observed "significant increases" in airport deterioration in the last 10 years.

Most airports experienced fewer than 20 flights per day. However, the population of the North is increasing (in particular in Nunavut, where the population growth between 2011 and 2016 was twice Canada's average[7])

[7] Statistics Canada. "Key Indicators – 2011-2016 Population Change %". [Online]. https://www12.statcan.gc.ca/census-recensement/index-eng.cfm?HPA=1

and most respondents noted that moderately increased airport traffic is expected in the future. Existing airport traffic consisted largely of prop planes for cargo and passenger services.

8.2.3 Climate Change Considerations

Ninety-six percent of respondents noted that climate change and its adverse impacts were recognized by their respective organizations. They expect the impact of climate change on northern airports to be moderate to severe. Respondents provided a text response giving their reason for choosing the severity of climate change impacts. Those results were compiled into a word cloud presented in Figure 7. Words with connotations of permafrost warming and ground ice thaw were significant in the word cloud.

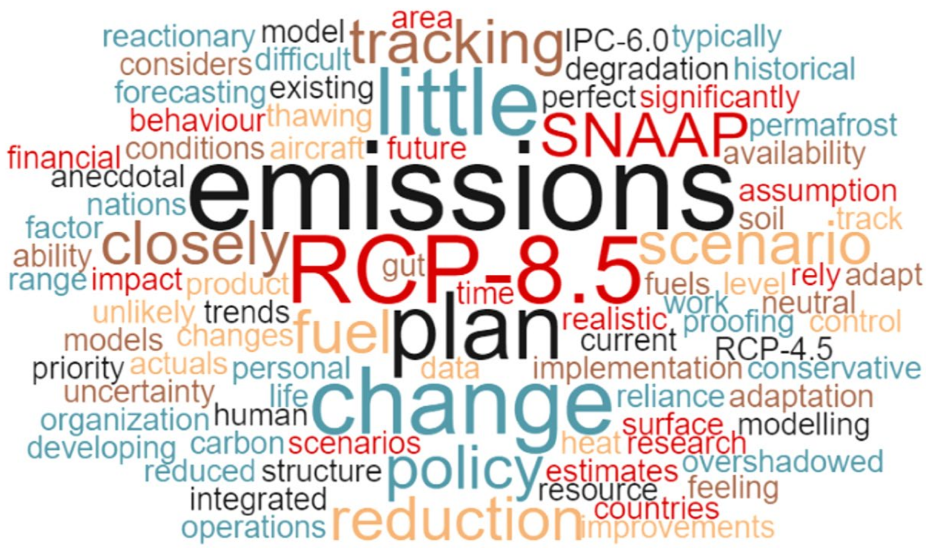
When asked which source they preferred to use for climate change projection data for any analyses, the respondents noted a preference for government or university climate centres (including Scenarios Network for Alaska and Arctic Planning, https://www.snap.uaf.edu/) with internal projections, or projections from a climate scientist specific to the project and literature. The respondents' organizations plan for little to no change in the rate of greenhouse gas emissions when considering climate change in infrastructure analysis and no standardization was identified in the criteria used for selecting the most appropriate model envelope and/or scenario. Both governmental and private sector respondents have participated in risk or vulnerability assessments but personal involvement in assessments for airports is less than organizational participation. The written responses describing the reason for the choice in emissions were summarized in the word cloud in Figure 8.

8.2.4 Risk and Vulnerability Assessments

The respondents from public and private sectors were asked a series of questions about their organizations' and their personal involvement in risk or vulnerability assessments for infrastructure. In general, respondents were aware of risk and vulnerability assessments that have been completed but respondents were less likely to have personal involvement in the assessments, and slightly more than half of the respondents had been involved in assessing an airport's infrastructure (Figure 9).

Figure 7: *Word cloud of responses to the question "Why did you choose the score for the question 'How adverse do you feel the impacts will be to the airport you interact with most?'"*

Figure 8: *Word cloud of responses to the question "Why did you choose the score for the question 'What degree of climate change does your organization plan for?'"*



As described in Section 3.1, the definition used in the assessment has an impact on the utility of the results and their interpretation. To this end, respondents were asked how the assessment defined risk and vulnerability (Figure 10). Definitions of vulnerability included the following terms, in decreasing frequency of respondents:

- Potential for a negative impact to occur;
- Likelihood of occurrence of a danger; and
- The ability to cope with or implement changes.

Risk was defined in three ways:

- A product of the probability and consequences of occurrence of a danger;
- The probability of occurrence of a danger; and
- The consequences of occurrence of a danger.

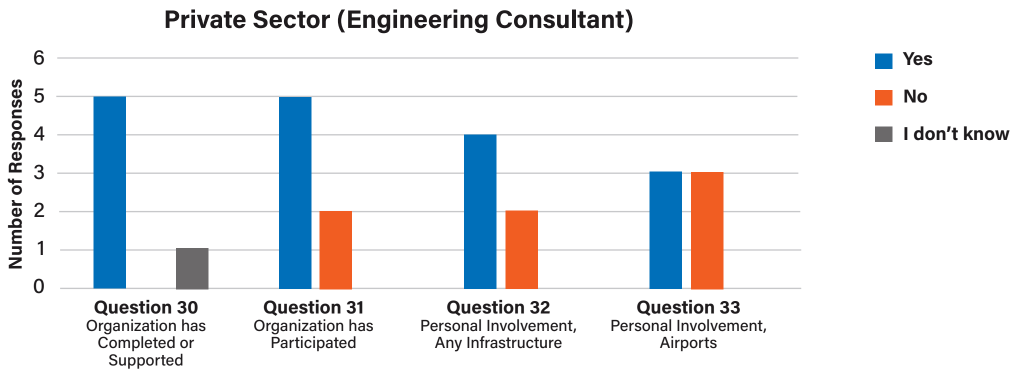
Note that these definitions overlap in one instance. Often, the PIEVC definitions were referred to explicitly by respondents. The PIEVC defines vulnerability in a manner consistent with the definitions presented in Section 3.1; however, the PIEVC does not use the same terminology for risk. In PIEVC assessments, this report's definition of risk is known as "engineering vulnerability". The PIEVC definition of "engineering vulnerability" includes both the likelihood of impacts to infrastructure and their consequences within the definition; thus, it resembles this report's definition for risk.

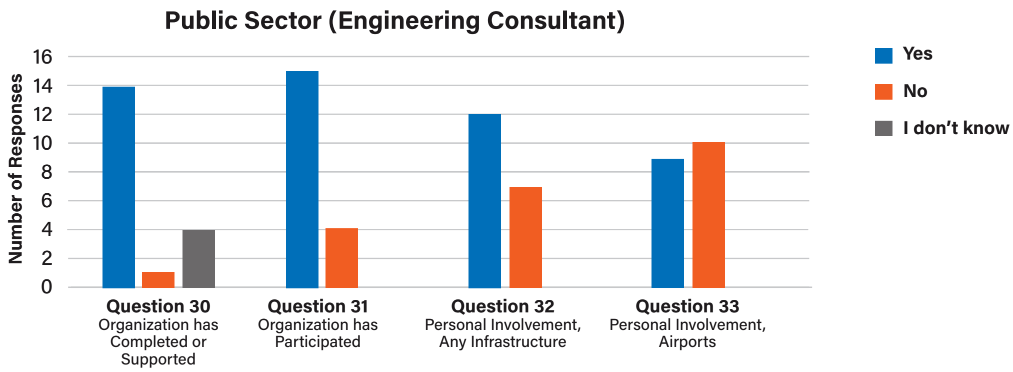
The methodologies used in the analysis also varied considerably. Seventy-five percent of respondents who were aware of the methodology used either original methods for vulnerability or risk analysis specific to the project, PIEVC methodologies, or hazard prediction. One respondent also noted the risk assessment method examined their organization's risk with regards to infrastructure interactions.

These assessments were generally focused on the physical infrastructure and not on the operations and maintenance of the airports. The elements of the airport included in the assessments are presented in Figure 11.

The inclusion of climate change projections into the risk and vulnerability assessments was reported by 70% of respondents for northern infrastructure, while 80% of respondents noted the risk or vulnerability assessment was completed for infrastructure underlain by permafrost. When the analysis was completed, the four climate parameters resulting in the highest risks were air and ground temperatures, and precipitation as water and snow. Increases in air and ground temperature

Figure 9: *Responses regarding respondents' and their organizations' level of involvement in risk or vulnerability assessments: A) private sector respondents, B) public sector respondents*





and precipitation were noted by respondents as having adverse (heightened) impacts on infrastructure risk and vulnerability. Changes in wind speed or direction and storm surges seemed to be contextual and dependent on the location of the airport.

These climate parameters were included in the analysis of dangers to airport infrastructure and operations. The dangers most often included in any risk and vulnerability assessments included thaw settlement, drainage system issues with loss of serviceability (flow capacity), bearing capacity, side slope steepening, and rain on snow events in a secondary group. The dangers that were rarely included were thermal erosion, subsurface voids, and active layer detachment landslides. Additionally, airport operations, including visibility and potential weather closures, were not included, partly because the potential danger to airport operations was not highlighted in the questionnaire.

Figure 10: *Classifications of risk and vulnerability assessment methodologies summarized from descriptions of the methodologies*

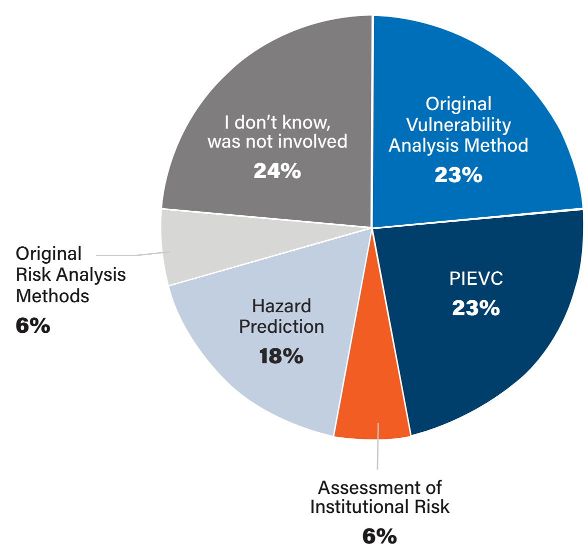
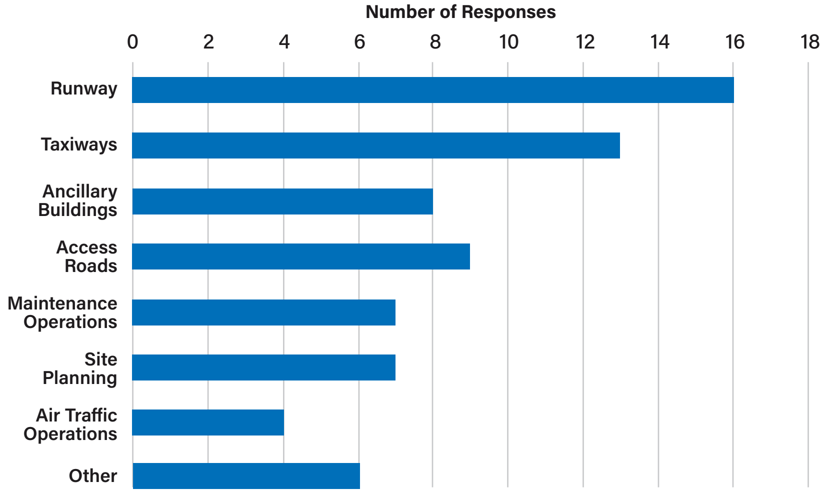


Figure 11: *Elements of airport infrastructure included in risk and vulnerability assessments*

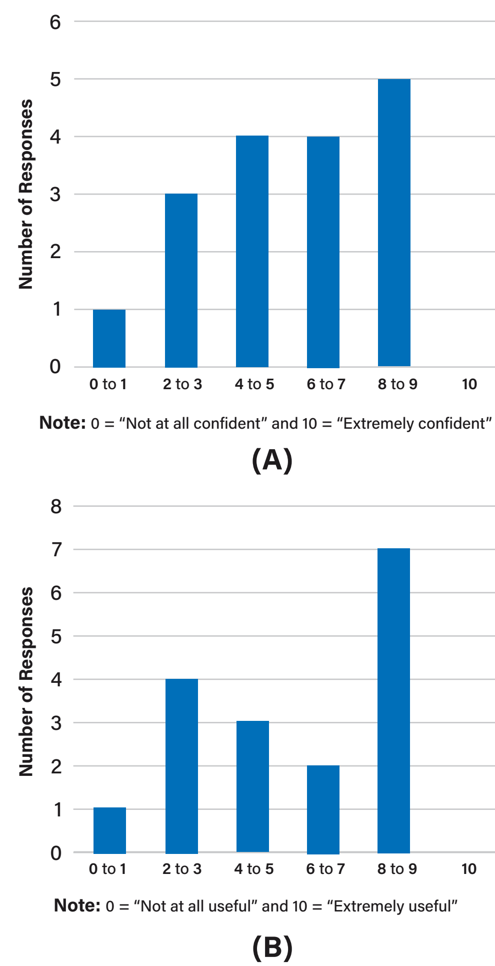


Once the risk and vulnerability assessments were completed, the respondents noted that there was mixed confidence in the results and their usefulness (Figure 12). The most common communication method for presenting the study results was a written report. These results aided decision-making for planning, capital improvements, and maintenance or management adaptations. In the case of some respondents, the assessment results were used in additional analyses such as decision-making analyses, observational analyses, or cost-benefit or cost-effectiveness analyses. Using the number of responses for each category, the methods most often used included cost-benefit or cost-effectiveness analyses, or decision-making methodologies.

The respondents were asked if there were any additional comments about risk and vulnerability assessments for northern infrastructure. The key points in the responses include the following:

- Participation in PIEVC risk assessment workshops are necessary. The respondent noted that due to the lack of participation, they didn't "feel like the key risks actually came to light."
- Risk and vulnerability assessments are "a very useful tool."

Figure 12: *Reported respondents' confidence (A) in the results and usefulness (B) of assessment results*



8.2.5 Need for a Standard

Among the respondents, there was moderate interest in the standard; 25% of respondents said a standard would be beneficial and an additional 25% noted that their interest in the standard depended on what was included within the analyses. The remaining 50% of the respondents' interest varied due to:

- Existing internal methodologies;
- Assessments are not conducted or are not often conducted;
- The choice of the standard is defined by the commissioning party; or
- Respondents would need to see if the standard was accepted before considering the methodology.

8.3 Discussion

Overall, the questionnaire was successful and met the goals of the study. The responses to the questionnaire highlighted the variability in the infrastructure, the operations, the types of assessments, the individual needs, and the utility of the results from a variety of perspectives. While the responses were not conclusive when considering individual answers only, the results show the need for a standard. Of the reported risk and vulnerability assessments that have been completed, the methodologies used do not provide sufficient guidance in two very important aspects:

1. Operations and maintenance activities are very difficult to include within the existing analyses' frameworks; and
2. Once the results become available, little is done.

The respondents of the questionnaire seemed to understand the utility of the results in relation to capital improvement projects and planning for the analyzed infrastructure. However, operations and maintenance activities will be the first line of defense in terms of adapting to climate change. For example, operations will be affected by climate change due to possible changes in prevailing wind directions and visibility, including ceiling height changes, fog prevalence, etc. Similarly, maintenance helps in preventing the deterioration of infrastructure and maintaining the required level of serviceability. However, neither were included in detail in a typical assessment.

Based on the feedback received, there seemed to be a disconnect in the respondents' use of and confidence in the risk and vulnerability assessments that were completed. Risk and vulnerability assessments are a relatively new tool and, depending on the methodology and the focus of the analysis, can have very different meanings. For example, vulnerability assessments alone only highlight dangers, hazards, or exposure to either or a combination of those. This differs from a risk assessment where the probability of occurrence and its consequence are combined. This again is not the same as assessing the resilience of a system or the infrastructure.

The stakeholder questionnaire indicates that a more holistic risk and vulnerability assessment standard should be created so that the points listed above are addressed in a systematic way and are less dependent on the experience and background of the professionals completing the assessment. This standard should consider the physical infrastructure and its underlying components, as well as the following components:

- The value of the infrastructure to the community;
- The changing demands of the airport (e.g., increasing traffic);
- The role of the airport within the larger northern transportation network;
- The operational conditions of the airport such as visibility (e.g., fog, ceiling height), wind direction, wind speed, whiteouts, surface icing, snow drifting;
- The types of aircraft using the airport (current and projected);
- Operations and maintenance requirements, including equipment (e.g., snowplows, de-icing, runway sanding) and materials (e.g., gravel source, sand, de-icing agent);
- The condition of the access road from the community to the airport; and
- The types of the risk or vulnerability assessment being used, their limitations and how to apply their findings for decision-making and further planning.

"From the assessments concluded to date, operations and maintenance have been identified as directly interacting with climate change in a way that results in high levels of risk for northern airports."

Without addressing the components listed above, a new standard may not have the breadth and depth to be widely accepted in practice and may not benefit the various stakeholders.

9.0 Recommendations and Conclusions

A total of 156 airports, of which 67 are located in the Yukon, Northwest Territories, and Nunavut, are situated within Canada's permafrost zones. Of these, 32% can be found in the region with continuous permafrost and 45% in regions with discontinuous permafrost. Most northern airports provide essential connections between communities with air travel being their only year-round option for the transport of people and goods. This study was initiated due to the critical nature of this infrastructure, and because it has not yet influenced decision-makers to systematically support and address the challenges associated with the current state of the infrastructure or its potential resilience to climate change. A literature review and a stakeholder questionnaire were conducted with the goal of determining the existing analysis methodologies for carrying out risk and vulnerability assessments for northern aviation infrastructure considering climate change. While some standards exist for the analysis of infrastructure supported by permafrost, little information is available specifically for northern airports, either pertaining to the physical infrastructure or to the operations and maintenance. Ongoing climate change (i.e., infrastructure deterioration, reductions in winter road seasons) and growing populations in northern communities will result in an increase in the importance of northern airports and consequently the need for resilience to future climate change.

The literature review showed that a small number of risk and vulnerability assessments has been completed to date. However, inconsistencies were identified regarding the assessment methods and associated definitions, the methodology for climate change data inclusion or addressing of climate change projection uncertainties. While the PIEVC protocol, developed under the auspices of Engineers Canada, has been used for northern airport infrastructure, the methodology is not specifically designed for the inclusion of operational and maintenance changes in light of impacts from climate change. From the assessments concluded to date, operations and maintenance have been identified as directly interacting with climate change in a way that results in high levels of risk for northern airports. Nevertheless, there seems to be a lack of action with regards to initiation of adaptation measures as a direct result of the assessments. This could be due to a deficiency in reporting on adaptation measures, not understanding the results, a shortage of funding necessary to act, insufficient confidence in the results, an absence of methods for adapting against climate change adaptation, or an absence of guidance.

Following the literature review, a stakeholder questionnaire was conducted via an online platform on the topic of risk and vulnerability assessments. The results of the questionnaire, which was completed by 27 individuals, including managers, researchers, designers, and regulators, confirmed that risk and vulnerability assessments on climate change are not uncommon (largely by organizations). However, the questionnaire results implied that the outcomes of the assessments are not being used to justify action. This lack of action may be due to multiple factors but likely stems from the subtle differences in the methodologies that affect the interpretation of the results. The results of existing assessments are focused on the airport's physical infrastructure, but a broader holistic analysis may be more beneficial to stakeholders.

Based on the literature review and the responses from stakeholders, which were confirmed during a project webinar held on May 13, 2020, it is recommended that a specific standard on climate change vulnerability assessments for northern airports should provide concrete guidance on:

- A consistent methodology for the analysis;
- Risk and vulnerability assessment specific terminology;
- Climate parameters and their projected changes that are tailored for short-term (day-to-day operations) and long-term (planning) needs;
- Consideration of uncertainties from the projections and operations (e.g., traffic volumes, aircraft types); and
- How to use the results in a decision-making process as well as in operations and maintenance.

It is important that the assessment not only pertains to the physical infrastructure of an airport but also addresses the full spectrum of operations and maintenance activities. This broader, holistic view ensures that the current and future demands of the airport are met, the resilience identified and the adaptation measures, if required, are provided in an adequate and timely manner. In particular in the North, adequate and well-timed planning is essential as it may take several years to implement certain measures. The widely accepted PIEVC methodology may provide a framework upon which a broadened assessment methodology can be built to provide a holistic analysis method for northern airport infrastructure.

In conclusion, the need for a standard in support of climate change risk and vulnerability assessments has been identified and this need should be specifically tailored for northern airport infrastructure and include the holistic view required for adequate adaptation planning.

References

[1] National Round Table on the Environment and the Economy, "True North: Adapting Infrastructure on Climate Change in Northern Canada," Report prepared for the Government of Canada, Ministry of Environment, Ottawa, ON, CAN, 2009.

[2] Deton' Cho Stantec, "'Change and Challenge': Climate Change Adaption Plan for the GNWT Department of Transportation," Report prepared for the Government of Northwest Territories, Department of Transportation, Yellowknife, NT, CAN, 2013.

[3] P. Pendakur, "Northern Territories," in *Climate Risks and Adaption Practice for the Canadian Transportation Sector 2016,* K. Palko and D.S. Lemmen, Eds. Ottawa, ON: Government of Canada, 2017, pp. 27–64.

[4] E. L'Hérault, M. Allard, C. Barrette, G. Doré, and D. Sarrazin, "Investigations géotechniques, caractérisation du pergélisol et stratégie d'adaptation dans un contexte de changements climatiques pour les aéroports d'Umiqujaq, Inukjuak, Puvirnituq, Akulivik, Salluit, Quaqtaq, Kangirsuk et Tasiujaq, Nunavik," Report prepared for the Bureau de la Corrdination du Nord-du-Québec, Ministère des Transports du Québec, Quebec City, QC, CAN, 2012.

[5] J. Boyle, M. Cunningham, and J. Dekens, "Climate Change Adaptation and Canadian Infrastructure: A Review of the Literature," International Institute for Sustainable Development, Winnipeg, MB, CAN, 2013. [Online]. Available: https://www.iisd.org/pdf/2013/adaptation_can_infrastructure.pdf

[6] I. Beaulac and G. Doré, "Permafrost Degradation and Adaptations of Airfields and Access Roads Nunavik, Québec, Canada," presented at the Annual Conference and Exhibition of the Transportation Association of Canada, Charlottetown, PEICAN, Sep. 2006. [Online].
Available: https://www.tac-atc.ca/en/conference/papers/permafrost-degradation-and-adaptations-airfields-and-access-roads-nunavik-quebec-canada

[7] M. Allard and M. Lemay, "Nunavik and Nunatsiavut: From Science to Policy: An Integrated Regional Impact Study (IRIS) of Climate Change and Modernization," ArcticNet Inc., Quebec City, QC,CAN, 2012. [Online]. Available: https://arcticnet.ulaval.ca//pdf/media/iris_report_complete.pdf

[8] T. Bell and T. Brown, "From Science to Policy in the Eastern Canadian Arctic: An Integrated Regional Impact Study (IRIS) of Climate Change and Modernization," ArcticNet Inc., Quebec City, QC, CAN, 2018. [Online]. Available: https://arcticnet.ulaval.ca//pdf/media/29170_IRIS_East_full%20report_web.pdf

[9] T. Heleniak, "Polar Peoples in the Future: Projections of the Arctic Populations," Nordregio, Stockholm, Sweden, Working Paper 2020:3, May 2020. [Online].
Available: https://nordregio.org/publications/polar-peoples-in-the-future-projections-of-the-arctic-populations/

[10] Office of the Auditor General of Canada, "Civil Aviation Infrastructure in the North – Transport Canada," 2017. [Online].
Available: https://www.oag-bvg.gc.ca/internet/English/att__e_42265.html

[11] R. van Everdingen, R. "Multi-language glossary of permafrost and related ground-ice terms". Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology. 1998, revised 2005.

[12] NAV Canada, "Canadian Airport Charts," May 21, 2020. [Online].
Available: https://www.navcanada.ca/EN/products-and-services/Documents/CanadianAirportCharts_Current.pdf

[13] J.A. Heginbottom, M.A. Dubreuil, and P.T. Harker, "Canada, Permafrost," The National Atlas of Canada, Natural Resource Canada, Geomatics Canada, MCR Series No. 4177, Ottawa, ON, CAN, 1995. [Online].
Available: https://ftp.maps.canada.ca/pub/nrcan_rncan/raster/atlas_5_ed/eng/environment/land/mcr4177.pdf

[14] PROLOG Canada, Inc., "The Northern Transportation Systems Assessment: Executive Summary," prepared for Transport Canada, Ottawa, ON, CAN, Jan. 2011. [Online].
Available: http://www.miningnorth.com/_rsc/site-content/library/ExecutiveSummary_E.pdf

[15] K. Schaefer, H. Lantuit, V.E. Romanovsky, and E.A.G. Schuur, "Policy Implications of Warming Permafrost," Report prepared for United Nations Environment Programme, Washington, DC, USA, 2012.

[16] Council of Canadian Academies, "Canada's Top Climate Change Risks: The Expert Panel on Climate Change Risks and Adaptation Potential," Ottawa, ON, CAN, 2019. [Online].
Available: https://cca-reports.ca/wp-content/uploads/2019/07/Report-Canada-top-climate-change-risks.pdf

[17] Airports Council International, "Airports' Resilience and Adaptation to a Changing Climate," Sept. 2018. [Online].
Available: https://store.aci.aero/wp-content/uploads/2018/10/Policy_brief_airports_adaption_climate_change_V6_WEB.pdf

[18] Intergovernmental Panel on Climate Change, *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change.* New York, NY: Cambridge Press, 2012.
Available: https://www.ipcc.ch/report/managing-the-risks-of-extreme-events-and-disasters-to-advance-climate-change-adaptation/

[19] Intergovernmental Panel on Climate Change, "Summary for Policymakers," in *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate,* H.O. Portner *et al.,* Eds., 2019. [Online].
Available: https://www.ipcc.ch/site/assets/uploads/sites/3/2019/11/03_SROCC_SPM_FINAL.pdf

[20] E. Bush and D.S. Lemmen, Eds., *Canada's Changing Climate Report.* Ottawa, ON: Government of Canada, 2019. [Online].
Available: https://changingclimate.ca/site/assets/uploads/sites/2/2020/06/CCCR_FULLREPORT-EN-FINAL.pdf

[21] Arctic Monitoring and Assessment Programme, *Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017.* Oslo, Norway: AMAP, 2017. [Online].
Available: https://www.amap.no/documents/doc/snow-water-ice-and-permafrost-in-the-arctic-swipa-2017/1610

[22] S.J. Hassol, *Impacts of a Warming Arctic: Arctic Climate Change Impact Assessment.* Cambridge, UK: Cambridge University Press, 2004.

[23] A. Instanes and J.L. Rongved, "Climate Change and Geotechnical Design in Permafrost and Frozen Ground," paper presented at the XVII European Conference on Soil Mechanics and Geotechnical Engineering, Reykjavik, Iceland, 2019. [Online].
Available: https://www.ecsmge-2019.com/uploads/2/1/7/9/21790806/0676-ecsmge-2019_instanes.pdf

[24] H. Brooks, "Quantitative Risk Analysis for Linear Infrastructure Supported by Permafrost: Methodology and Computer Program," Ph.D. dissertation, Depart. Civil and Water Eng., Univ. Laval, Quebec City, Quebec, CAN, 2019.

[25] F. Calmels, G. Doré, X. Kong, L.P. Roy, C. Lemieux, and B. Horton, "Vulnerability of the North Alaska Highway to Permafrost Thaw: Design Options and Climate Change Adaptation," Northern Climate ExChange, Yukon Research Center, Yukon College, Whitehorse, Yukon, Canada, 2016. [Online].
Available: http://scholar.yukonu.ca/sites/default/files/bhorton/files/ah_yr4_report_finalproof_web.pdf

[26] B.M. Ayyub *et al., Adapting Infrastructure and Civil Engineering Practice to a Changing Climate.* Reston, VA: ASCE, 2015.
Available: https://ascelibrary.org/doi/pdf/10.1061/9780784479193

[27] CSA Group, "Infrastructure in Permafrost: A Guideline for Climate Change Adaptation," Technical Guide CSA PLUS 4011:19, 2019.

[28] CSA Group, "Technical Guide: Design and Construction Considerations for Foundations in Permafrost Regions," Technical Guide CSA PLUS 4011.1:19, 2019.

[29] B. Biskaborn *et al.,* "Permafrost Is Warming at a Global Scale," *Nat. Commun.,* vol. 10, no. 1, Jan. 16, 2019, https://www.nature.com/articles/s41467-018-08240-4

[30] H. Auld, "Adaptation by Design: The Impact of Changing Climate on Infrastructure," *J. Public Works Infrastruct.,* vol. 1, pp. 276–288, Jan. 2008.

[31] J. Hanski, J. Keränen, and R. Molarius, "Tools and Methods for Supporting Regional Decision-Making in Relation to Climate Risks," in *Climate Change and Global Warming,* A. Amini, Ed., 2018. [Online].
Available: https://www.intechopen.com/books/climate-change-and-global-warming/tools-and-methods-for-supporting-regional-decision-making-in-relation-to-climate-risks

[32] World Federation of Engineering Organizations, "Model Code of Practice: Principles of Climate Change Adaptation for Engineers," WFEO Committee on Engineering and the Environment, Dec. 2015. [Online].
Available: https://www.wfeo.org/wp-content/uploads/code-of-practice/WFEO_Model_Code_of_Practice_Principles_Climate_Change_Adaptation_Engineers.pdf

[33] National Academies of Sciences, Engineering, and Medicine, "Using Existing Airport Management Systems to Manage Climate Risk," Airport Cooperative Research Program (ACRP) Research Report 188, Washington, DC, USA, 2018.

[34] Engineers Canada, "Public Guideline: Principles of Climate Adaptation and Mitigation for Engineers," May 2018. [Online].
Available: https://engineerscanada.ca/publications/public-guideline-principles-of-climate-change-adaptation-for-professional-engineers

[35] Engineers Canada, "Public Infrastructure Engineering Vulnerability Committee (PIEVC) Protocol" Institute for Catastrophic Loss Reduction, Toronto, 2016.

[36] Public Safety Canada, "All Hazards Risk Assessment: Methodology Guidelines 2012-2013," 2012. [Online].
Available: https://www.publicsafety.gc.ca/cnt/rsrcs/pblctns/ll-hzrds-ssssmnt/ll-hzrds-ssssmnt-eng.pdf

[37] F. N. Tonmoy, D. Rissik, and J.P. Palutikof, "A Three-Tier Risk Assessment Process for Climate Change Adaptation at a Local Scale," *Clim. Change,* vol. 153, pp. 539-557, Feb. 4, 2019,
https://doi.org/10.1007/s10584-019-02367-z

[38] S. Lacasse, F. Nadim, and K. Høeg, "Risk Assessment and Mitigation in Geo-Practice," in *Geotechnical Engineering State of the Art and Practice: Keynote Lectures from GeoCongress 2012.* Oakland, CA: ASCE, 2012, pp. 729–764.
Available: https://doi.org/10.1061/9780784412138.0026

[39] A. Lopez, "Vulnerability of Airports on Climate Change: An Assessment Methodology," *Transp. Res. Procedia,* vol. 14, pp. 24–31, 2016.

[40] G.B. Baecher and J.T. Christian, *Reliability and Statistics in Geotechnical Engineering.* Chichester, West Sussex, UK: John Wiley and Sons, 2003.

[41] S. Lacasse and F. Nadim, "Learning to Live with Geo-Hazards: From Research to Practice," in *GeoRisk 2011: Geotechnical Risk Assessment and Management,* Atlanta, GA: ASCE, 2011, pp. 64–116.
Available: https://doi.org/10.1061/9780784411834

[42] ICF, "Strategic Climate Risk Assessment Framework for British Columbia: Developed in Progress Toward a Strategic Climate Risk Assessment for British Columbia," Report prepared for the Ministry of Environment and Climate Change Strategy, Victoria, BC, CAN, 2019.

[43] F. Calmels *et al.,* "Vulnerability of the north Alaska Highway to Permafrost Thaw: A Field Guide and Data Synthesis," Northern Climate ExChange, Yukon College Research Centre, Yukon College, NWT, CAN, 2015.

[44] UAF, USACE, CRREL, "Statewide Threat Assessment: Identification of Threats from Erosion, Flooding, and Thawing Permafrost in Remote Alaska Communities," University of Alaska Fairbanks, US Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Report prepared for the Denali Commission INE 19.03, Anchorage, AK, USA, 2019.

[45] BGC Engineering Inc., "Cambridge Bay Airport – Climate Change Vulnerability Assessment," Report prepared for Transport Canada, Ottawa, ON, CAN, May 2016.

[46] BGC Engineering Inc., "Churchill Airport – Climate Change Vulnerability Assessment," Report prepared for Transport Canada, Ottawa, ON, CAN, May 2016.

[47] BGC Engineering Inc., “Mike Zubko Airport – Climate Change Vulnerability Assessment,” Report prepared for Transport Canada, Ottawa, ON, CAN, May 2016.

[48] BGC Engineering Inc., “Highway 3 – Climate Change Vulnerability Assessment,” Report prepared for the Government of Northwest Territories, Department of Transportation, Yellowknife, NWT, CAN, 2011.

[49] National Academies of Sciences, Engineering, and Medicine, “Climate Resilience and Benefit Cost Analysis: A Handbook for Airports,” Airport Cooperative Research Program (ACRP) Research Report 199, Washington, DC, USA, 2019.

[50] National Academies of Sciences, Engineering, and Medicine, *Transportation Resilience: Adaptation to Climate Change.* Washington, DC: The National Academies Press, 2016.

[51] H. Auld, D. MacIver, and J. Klaassen, “Adaptation Options for Infrastructure Under Changing Climate Conditions,” paper presented at the 2006 IEEE EIC Climate Change Conference, Ottawa, ON, CAN, May 2006. [Online]. Available: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=4057378&refinements%3D4223176451%26filter%3DAND%28p_IS_Number%3A4057291%29

[52] R. Burbidge, “Adapting European Airports to a Changing Climate,” *Transp. Res. Procedia,* vol. 14, pp. 14–23, 2016.

[53] A.C. Hill, D. Mason, J.R. Potter, M. Hellmuth, B. Ayyub, and J.W. Baker, “Ready for Tomorrow: Seven Strategies for Climate-Resilient Infrastructure,” Hoover Institution, 2019. [Online]. Available: https://www.hoover.org/sites/default/files/research/docs/hill-ready-for-tomorrow-seven-strategies-for-climate-resilient-infrastructure_0.pdf

[54] National Academies of Sciences, Engineering, and Medicine, “Airport Climate Adaptation and Resilience,” Airport Cooperative Research Program (ACRP) Synthesis 33, Washington, DC, USA, 2012.

[55] R.V. McGregor, M. Hassan, and D.W. Hayley, “Climate Change Impacts and Adaptation: Case Studies of Roads in Northern Canada,” paper presented at the 2008 Annual Conference of the Transportation Association of Canada, Toronto, ON, CAN, Sep. 2008. [Online]. Available: http://conf.tac-atc.ca/english/resourcecentre/readingroom/conference/conf2008/docs/a1/mcgregor.pdf

[56] Economic Commission for Europe, “Report of the Group of Experts on Climate Change Impacts and Adaptation for Transport Networks and Nodes,” United Nations Economic Commission for Europe – Inland Transportation Committee, Working Party on Transport Trends and Economics, Report – Informal Document W.P. 5, 2019.

[57] A. Christodoulou and H. Demirel, “Impacts of Climate Change on Transport: A Focus on Airports, Seaports and Inland Waterways,” EUR 28896 EN, Publications Office of the European Union, Luxembourg, 2018. Available: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC108865/jrc108865_final.pdf

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