Enhancing knowledge transfer to decision-makers

with respect to climate change impacts on the cryosphere

Northern Climate ExChange
YUKON RESEARCH CENTRE • Yukon College

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EXECUTIVE SUMMARY

The goal of the project was to identify and understand the snow- and permafrost-related information needs of practitioners in the mining and transportation sectors in northern Canada, specifically in Yukon and the Northwest Territories, and to produce knowledge products that respond to a subset of those needs to encourage adaptation to climate change.

Mining and transportation practitioners from various backgrounds identified the need for:

- Case studies of infrastructure failures and adaptations.
- Easily accessible and tailored climate hazards-related information.
- Guidance on the complex interplay of climate elements such as snow and permafrost, rain on snow, etc.
- Practical and user-friendly climate-change guidance and tools including best practices, outreach materials, financial justifications for adaptation, etc.
- Accessible training on climate and weather impacts, permafrost, and other related topics for practitioners and decision-makers.

The project resulted in the development of a web-based tool that responds to the need for case studies of infrastructure failures and adaptations, with the ultimate goal of providing information that will help practitioners incorporate successful adaptations. The *Climate and Infrastructure Forensic Analysis System* (CIFAS) is both an online database of infrastructure and climate events and a forensic analysis system. The system is populated with events affecting infrastructure in northern Canada and the climate, infrastructure and engineering data surrounding those events, as well as adaptations that were applied both successfully and unsuccessfully.

The second product is a set of case studies and automated reports that are an extension of the first product, CIFAS. The case studies are guidance documents to show how CIFAS can be used to generate an in-depth case study of an infrastructure failure, with the goal of identifying adaptation options to prevent those failures in the future. At the same time, the two case studies that were generated for this project provide specific examples of in-depth case studies related to infrastructure and climate change. While the case studies are complex and require further analysis, the automated reports that CIFAS could generate can help identify potential climate impacts threshold values and other trends. CIFAS will be able to generate two types of automated report: 1) *single incident* reports that focus on an individual event and/or piece of infrastructure; and 2) *cross-incident* forensic analyses that refer to either multiple incidents or pieces of infrastructure grouped together by one or more common characteristics, such as geographical region, infrastructure element type (e.g., access road, culvert, municipal road) or climate/meteorological driver (e.g., rain-on-snow event, active layer thaw).

A key element in the success of this project was the role of the stakeholder and the amount of engagement that occurred throughout the process. Industry practitioners, professional organizations, government representatives and other key decision makers were engaged in developing the scope of the literature review, in prioritizing and refining the products and in identifying options for the dissemination strategy.

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1. INTRODUCTION

The project "Enhancing Knowledge Transfer to Decision Makers with Respect to Climate Change Impacts on the Cryosphere", hereafter known as the Cryosphere Project, focuses on consolidating and identifying gaps in our current knowledge, as well as understanding and providing awareness of the impacts of northern climate change on permafrost and snow in the northern mining and transportation sectors. The goal of the project is to identify the snow- and permafrost-related information needs of practitioners in the mining and transportation sectors in northern Canada, specifically in Yukon and the Northwest Territories, and to produce knowledge products that respond to those needs.

Researchers from the Northern Climate ExChange and Risk Sciences International were the main leaders in developing products that respond to the climate and weather-related needs of practitioners and decision makers whose professions are directly impacted by climate and weather. Additional organizations making up the Project Team include University of Ottawa, OCCIAR, and Government of Northwest Territories Department of Transportation.

2. BACKGROUND

Evolving conditions in the Canadian North (herein referred to as the North) driven by climate change will directly result in changes to the northern cryosphere. Present climate conditions across much of the North appear to have already changed significantly from the recent past, and have resulted in discernible effects on key elements of the cryosphere, including permafrost, snowpack, snowfall and other forms of frozen precipitation, river and lake ice, and ocean ice. These impacts to the cryosphere have begun to affect a range of human activities across the North, including the private sector and northern industries.

To help reduce risks stemming from these impacts, it will be important to address the consolidation, development and dissemination of relevant and trusted knowledge with respect to the effects of climate change on elements of the cryosphere. Depending on the potentially impacted party or activity, different cryosphere and climate change-related information may be desired, with respect to different geographies, timeframes, decisions, sensitivities, stakeholders and industry sectors, and parameters and thresholds.

Two areas of private sector activity that will be increasingly affected by the impacts of climate change on the cryosphere are the mining and ground-based transportation sectors. Many aspects of both sectors are reliant on understanding, planning, designing and managing systems in order to account for the character of elements of the cryosphere, including permafrost and snow. Permafrost is present in many northern mining environments, and changing permafrost conditions must be assessed with respect to their potential impacts on everything from the long-term viability of retention facilities to site accessibility. Meanwhile, the ground-based transportation sector, whether concerned with designing and maintaining private (e.g., mining) access or public-use roads, must be vigilant about the potential for permafrost-related impacts, due to the long distances and lack of redundancy of ground-based transportation networks, and the widespread presence of permafrost across the North.

Snow is of consequence for the mining and ground-based transportation sectors for a number of reasons. First, snow can significantly affect the temperature regime and behavior of underlying permafrost; it acts as an insulator in the winter, reducing the degree to which the active layer freezes back, while in the spring snow produces meltwater which, through pooling or percolation, acts to warm the ground. Second, both snow-on-the-ground and snowfall events can result in significant impediments to a range of operations in both sectors. Third, the contribution of snowpack to flooding events can be significant, and will vary based on a range of factors, including key characteristics of the snow and the timing and rate of melt events. Finally, snow overload can pose risks to critical structures.

This project will serve as a pilot for a more comprehensive set of future climate change adaptation decision-support products, as well as knowledge development and transfer exercises. It will assess existing evidence of changing permafrost and snow conditions. Furthermore, it will provide information on future climate change projections, in order to develop and test information and communication products for climate change adaptation decision-making in the northern mining and ground-based transportation sectors.

While there is a need for products that address all elements of the cryosphere and all areas of the geographic North, the scope of this project was narrowed to focus on permafrost and snow in Yukon and the Northwest Territories (NWT). The products however are useful for the entire Canadian North and can be expanded to include other climatic elements.

Project objectives were to:

- assess and identify gaps in existing knowledge, understanding and awareness of the impacts of northern climate change on permafrost and snow, accounting for the relevancy (including credibility and usefulness) of existing information for adaptation decision-making by private sector players involved in mining and ground-based transportation;
- engage with the primary stakeholders in order to understand in specific terms their highest priority knowledge requirements with respect to climate change impacts on permafrost and snow;
- prepare communication materials ('knowledge products') and a related dissemination strategy based on the above, which is targeted to, and tailored for, the above-noted sectors and decision-makers;
- assess and recommend additional courses of action that may be required in order to meet the needs or enhance the transfer of knowledge to the above-noted sectors and decision-makers; and,
- present and disseminate the knowledge products to private-sector players in the mining and ground-based transportation sectors, as well as to other relevant practitioners.

3. METHODOLOGY

While the methodology and work plan for the project were laid out in the proposal, the Project Team included an iterative aspect to the project which allowed for some flexibility to make changes as necessary based on the advice and feedback of Project Team and Project Advisory Committee members.

3.1. Project Development and Project Advisory Committee

A Project Advisory Committee (PAC) was struck early on to guide project development including the literature review, practitioner interviews and reporting, as well as to provide feedback throughout the development of the knowledge products and dissemination strategy. The PAC was composed of private-sector representatives and users of cryosphere information from the mining and ground-based transportation-related industries (including consulting engineers), as well as regulatory bodies, related government departments, and climate and permafrost research communities.

As the project developed, the Project Team found that some PAC members could devote more time to the project than others, and new advisors became involved throughout the life of the project. In particular, as the process moved towards soliciting targeted feedback from practitioners the number of people involved as advisors grew. Soliciting individualized feedback through this process resulted in more effective and relevant engagement of advisors than using a traditional committee meeting format.

3.2. Identification and Characterization of Priority Information Needs & Key Sources

The next phase of the project involved identifying and prioritizing industry information needs and key sources. A survey of the literature was conducted in order to assess the availability and coverage of information, the availability of data, and efforts required and challenges posed with respect to the development of useable products. The literature review helped inform the development of the interview guides and the identification of eventual respondents.

3.2.1. Literature Review

A literature review was completed to inform other elements of the project, including development of an interview guide, identification of project advisors and interview respondents, and development of knowledge products. This process consisted of an evaluation and assessment of existing knowledge regarding priority climate-change impacts on permafrost and snow conditions through reviewing a targeted collection of peer-reviewed and grey literature. Grey literature sources included unpublished and internal government reports, northern research institute reports, online information repositories, industry or regulatory reports, and key standards and guidelines. The literature review was focused on answering the following questions:

- What snow and permafrost data is currently available in a format the sector requires and can be developed or 'packaged' without significant effort?
- What snow and permafrost information may be available through the literature or other sources but has yet to be consolidated, presented, vetted or regionalized in ways the sector may require?
- What snow and permafrost information requires significant efforts to develop or may lack sufficient observations or data for further development?
- Are there any specific obstacles to developing key aspects of the information that either of the targeted sectors are requesting?
- What tools are currently available to help meet the information requirements of the sectors?
- Are there any particular practices, models, standards or guidelines to guide the development of the required information products, the blending of datasets of variable qualities, use of anecdotal impacts information, etc.? And what noteworthy limitations exist with respect to these 'tools'?

The findings from the literature review were summarized in a report (Appendix C) and were presented to the PAC, Project Team and other practitioners at Webinar 1. The findings were used with the interview results to identify priority information needs and potential knowledge products.

3.2.2. *Interviews*

An interview guide was developed by the Project Team to ensure consistency and structure during the interview process. Originally, interviews were to be addressed separately between snow and permafrost experts. However, this approach was rapidly abandoned when it became clear that practitioners may not differentiate between those two elements, and that they are in fact highly correlated in some cases (e.g., impact of snow on surface energy balance and the permafrost active layer). Two versions of the guide, nearly identical in nature, were eventually developed for the mining and transportation sectors. It was also found that a semi-structured interview approach, tailored to the individual practitioner, was much more effective than pre-determining or compartmentalizing content prior to the interview.

Development of the interview guide was done iteratively, with the guide going through several modifications based on feedback from the Project Advisory Committee and the first few interviews. In particular, the interview guide was shortened significantly following the first interview. It eventually consisted of seven (7) multi-part questions, which were further separated into two main components: climate hazard and risk identification, and knowledge product discussion. An additional four ‘soft’ or non-technical questions addressing climate change and adaptation knowledge were displaced to the end of the form. These non-technical questions were set aside and only addressed when time allowed due to both their secondary nature with respect to project goals, as well as concerns over the time required to conduct the survey.

Interviews were conducted in teams of two and consisted of one or more practitioners as interviewees. While the original intent had been to interview practitioners on an individual basis, interviews in which multiple people were interviewed tended to produce very good results, since co-workers were given a chance to discuss subject matter and exchange ideas while answering questions. It also made the interview process more efficient, allowing for a greater number of practitioners to participate in the project.

The interview team consisted of researchers from the Northern Climate ExChange, Risk Sciences International, Mirarco, and the Government of the Northwest Territories’ Department of Transportation. Interviews were conducted by phone, with one of the interviewers asking questions while the second recorded notes. Interviews were recorded for the purpose of verifying responses and filling information gaps in the transcripts where required. The original intent was to conduct interviews in person whenever possible; however, it became clear that it was more practical to conduct interviews by phone, as many of the interview participants had time constraints and interviews were often coordinated between various locations and time zones.

3.2.2.1. Participants

A total of 18 interviews were conducted, including 7 representatives from the mining sector, 8 representatives from the transportation sector, and 3 representatives who work with both the mining and transportation sectors. Of the 18 respondents, 4 respondents work for mining companies, 8 work for consulting firms that work with the mining and transportation sectors, and 6 work for government agencies involved in the ground-based transportation industry, specifically employees of the Yukon and Northwest Territories governments. Almost all of the respondents have 15 years or more experience working in the North in their respective sector, with many having at least 25 to 30 years. Participants were from Yukon Zinc Corp., Victoria Gold Corp., Alexco Resources Corp., BGC Engineering Inc., Tetra Tech EBA, Naviq Consulting Inc., Yukon Government Highways and Public Works, and the Government of Northwest Territories (GNWT) Department of Transportation.

3.2.3. Webinar 1: Climate Change, Permafrost and Snow: Investigating Impacts on Mining and Ground-Based Transportation and Resultant Information Needs in Yukon and Northwest Territories

A webinar was held on April 17, 2013 to discuss the preliminary findings from the literature review and practitioner interviews, including a list of information needs resulting from the research. The goal of the webinar was to gather further information from sector and other technical experts, as well as receive feedback from the members of the Project Advisory Committee (PAC) on the information needs and potential knowledge products. The webinar attendees included PAC members, Project Team members, and several practitioners identified through the interview process. The webinar was facilitated by John Streicker, Science Advisor for the Northern Climate ExChange. Presentations by Simon Eng from Risk Sciences International and Alison Perrin from the Northern Climate ExChange provided results from the literature review on snow loads and permafrost, and results from the practitioner interviews, respectively, as well as a summary of the industry needs and suggested knowledge products. Participant discussion focused on the refinement of the suggested industry needs and knowledge products, as well as suggestions on possible improvements to the literature review. The webinar presentations and results were summarized in a separate report submitted to NRCan.

3.3. Development of Knowledge Products and Dissemination Strategy

A list describing potential knowledge products was circulated to the Project Advisory Committee and other experts from both the transportation and mining sectors. The Project Team gathered feedback from these practitioners to narrow the list to two knowledge products that could feasibly be produced in the timespan of this project. The list of products that will not be produced as part of this project is provided as a set of recommendations for future knowledge products to the project funder.

3.3.1. Knowledge Products

Two knowledge products were developed through an iterative process incorporating targeted feedback from industry practitioners; Product 1: the Climate and Infrastructure Forensic Analysis System (CIFAS) and Product 2: CIFAS case studies and automated reports. As the products were developed, members of the Project Team contacted practitioners to solicit advice and feedback. Through this process, the list of advisors involved in the project grew to include new members. This targeted feedback process helped the Project Team further refine the scope and parameters of the products and proved invaluable as a means for raising awareness regarding the eventual products, as further discussed below.

3.3.2. Dissemination Strategy

A dissemination strategy was developed concurrently with the knowledge products, and as mentioned above, was a key element in the iterative process used to refine the knowledge products. The dissemination strategy includes the targeted feedback used in product development, suggested formats and platforms for the knowledge products, and key organizations that were part of the development and could be integral to the future dissemination of the products.

3.3.3. Testing and Refinement of Knowledge Products and Dissemination Strategy

In the original proposal, a one-day workshop was proposed as a means of testing and refining the knowledge products and dissemination strategy. However, as described in the dissemination strategy, a targeted feedback approach was used to test and refine the products and because of this, it was decided that it would be more effective, and a better use of resources, to give a presentation on the products at the Transportation Association of Canada (TAC) conference in Winnipeg on September 21, 2013. Project Team member Heather Auld presented to the TAC Engineering and Research Support Committee's Northern Transportation Infrastructure in the Presence of Climate Change Subcommittee. While lack of time prevented a fulsome discussion of the products, the TAC audience was interested in the potential use of CIFAS for maintenance, safety and climatic design considerations, as well as the potential for possible detection of climate thresholds or infrastructure breaking points. The subcommittee was also encouraged to see multi-disciplinary work being done on adaptation research with practical applications.

3.3.4. Webinar 2: Draft Knowledge Products and Dissemination Strategy

A webinar was held on September 24th, 2013 to discuss the draft knowledge products and associated dissemination strategy. The goal of the webinar was to solicit feedback from the members of the Project Advisory Committee (PAC), the project team, and other project advisors and participants on the format, content and dissemination of the knowledge products in order to further refine them. The webinar attendees included PAC members, Project Team members, and government representatives. The webinar was facilitated by John Streicker, Science Advisor for the Northern Climate ExChange. Presentations provided an introduction to the knowledge products and the dissemination strategy. Participant discussion following the presentations focused on finding a location for hosting CIFAS, as well as strategies for disseminating and expanding the products. Participants were supportive of the products and their relevance to northern decision-makers. The webinar presentations and results were summarized in a separate report submitted to Natural Resources Canada (NRCan).

4. Discussion of Results

4.1. Literature Review

The literature review focuses on the impacts of snow and permafrost, and their effects on surface transportation and the mining sector in the Canadian north, namely Yukon and the Northwest Territories. A Literature Review Report was prepared to share results (Appendix C). This report introduces definitions of the main components of the research project as well as their parameters. It reviews climate interactions with both snow and permafrost including expected future changes. Regarding the mining and transportation sectors, the report includes a discussion of the relative importance of climate change impacts, the benefits and limitations of related adaptation measures, and gaps and limitations in available knowledge and research. The report also includes a review of climate-permafrost interactions, permafrost distribution modelling, and climate change impacts on mining and transport infrastructure in the North.

4.2. Interview Synopsis

4.2.1. Hazards

4.2.1.1. Permafrost

Permafrost was listed by all respondents as a hazard that they experience and plan for in their work. Challenges raised included challenges in identifying the location and type of permafrost, infrastructure design lifespan, construction in a permafrost environment, slope stability issues, and projecting change in underlying permafrost conditions during the service life of the structure and designing accordingly.

In many areas of the North, it can be assumed that permafrost exists and should be planned for. However, in most of Yukon and parts of the Northwest Territories, there are areas of discontinuous permafrost (areas where 30-80% of the ground surface is underlain by permafrost). For people working in these regions it becomes necessary during the planning stages to determine where permafrost exists. Some respondents in both sectors conducted expensive site investigations, including drilling boreholes to determine where permafrost exists. The cost of site-specific investigations can be prohibitive and many respondents from the mining sector used qualitative scientific techniques to predict where permafrost would most likely be present (e.g., permafrost is common on north-facing slopes, in valley bottoms, and at higher altitudes).

Respondents involved in infrastructure design in both the mining and transportation sectors were concerned with surface infrastructure design, and how infrastructure will perform over its expected lifetime. Mining infrastructure, except for tailings, is generally designed for the life of the project which can be less than 20 years. Transportation infrastructure is usually designed for a longer lifespan, generally 50 years. Two of the respondents in the transportation sector mentioned the difficulty of predicting change over a 50-year span, thus posing a challenge in the design process. Most of the respondents in both sectors use climate trends and 'worst case scenarios' in planning and design, and some use climate projections. Several respondents said that the data they are working with is the best available, but is still quite limited. Many of the respondents communicated a concern regarding the impact of unexpected weather events, such as severe rainstorms, on permafrost and infrastructure.

In regions with colder temperatures and colder permafrost, tailings containment can be designed to be dependent on permafrost remaining frozen, such as frozen core dams. Several respondents expressed concern over the planned lifetime of these designs. One respondent expressed that "we need to look farther in the future when we predict how the permafrost will hold up". Another stressed that tailing deposits should be designed for perpetuity, the challenge being design for unknown future risk. One respondent recommended removing all water from tailings and using dry stack tailings to avoid issues with containing tailings ponds. Another identified reclamation and abandonment, including the short lifespan of remediation techniques, and the associated costs to tax payers, as the most important issue facing the northern mining industry.

Concerns were expressed about the disturbance of permafrost associated with the construction of infrastructure. In Yukon where most of the permafrost is warm and discontinuous, there was a range of techniques being used to manage permafrost in the mining industry. One respondent working with Yukon mines uses disturbance as a way of managing the warm permafrost before beginning the construction phase. Another respondent working in an area of discontinuous permafrost used extensive analysis of permafrost to avoid disturbing permafrost on the site. Several respondents emphasized the importance of not disturbing the permafrost, and discussed the difficulty of dealing with thawed permafrost following disturbance. One mine operation uses a variety of materials on access roads to minimize these issues, including coconut matting, permafrost seeps, and rip rap. One respondent discussed discovering permafrost during the construction phase and then adapting plans to move planned roads or infrastructure to avoid the permafrost.

Some respondents felt that it was important to keep the ground frozen during the construction of infrastructure and during the life of that infrastructure. For ground-based transportation, this is a major challenge and there are a variety of studies and test sites that focus on techniques to maintain ground temperature under and around roads. Several respondents from both sectors mentioned the importance of continuing to monitor soil stability and temperature once the mine or road was operational following construction.

Permafrost thaw can induce settlement and stability issues which are major concerns for respondents involved in transportation planning and maintenance, as well as infrastructure planning and maintenance for mines. Respondents were concerned with changes to the active layer thickness in both sectors and throughout Yukon and the Northwest Territories. Site access is an operational hazard in areas with extensive permafrost, as consistent access may only be possible during the coldest season. One respondent claimed that the “cold season” has been shorter for the last ten years, impacting site access for their operations.

As one respondent pointed out, mining operations are generally short term, often having a lifespan of 15 to 20 years, so they may not experience large-scale changes during that time. However, as several of the mining sector respondents voiced, mines can experience slope stability issues and landslides, as has happened in the Mackenzie River area. These can impact mining operations and are a major safety issue. Landslides are also a concern for ground-based transportation, as experienced in Yukon in 2012 when landslides occurred on three major highways during the same time period and impacted access to goods.

4.2.1.2. Snow

While snow loads were part of the focus of this study, the main snow-related hazard that was identified by representatives from both the mining and transportation sectors was the impacts of increased amounts of precipitation, including both rain and snow. Related to increased snow were other issues such as runoff, increased snow layer on ice and permafrost, minimized visibility, and avalanches. Several respondents mentioned that if they could plan for seasonal snowfall amounts, it would improve their ability to manage it more economically. While it is currently difficult or impossible to predict how much snow to expect and when to expect it, or when spring runoff will occur, this is an indication of where additional work and research is greatly needed.

Increased snow is generally disruptive to the work flow of a mine. It makes mine site operations harder to manage, including simply locating equipment, access points and pipes beneath snow cover. Some operations manage snow by moving it around and removing it from areas of concern, however this increases costs. This can be done to manage snow around infrastructure and roads, and to avoid increased runoff, or to remove snow from areas where permafrost is a concern.

More snow and rain can have severe implications for mines as the water balance profile is a major challenge for mine operations. Unusually high snow years and early spring warming have caused increased erosion, debris chutes and landslides. Some operations have tried to mitigate erosion by seeding and vegetating exposed slopes with varying success. Runoff can make it difficult to limit the amount of water that contacts tailings, which increases the amount of water that needs to be treated and increases costs for the mine. In extremely high water years, this can lead to emergency water releases. Runoff also brings silt and sediment into the tailings. One solution is to actively manage the water movement around the site through building diversion ditches for excess run off.

The impact of water and runoff on permafrost is also a concern to both the mining and transportation sectors. The interplay between ground water and permafrost was mentioned as a major concern by respondents and is one of the main reasons for diverting runoff or managing snow loads. One respondent was concerned that many mine hydrologists lack the ability to predict run off in a permafrost environment.

Increased snow can also have an impact on permafrost by insulating the ground and increasing ground temperatures, particularly in areas where deep snow drifts form. Modelling how snow accumulates around a structure can help to identify where it will accumulate and how to plan infrastructure appropriately. Runoff can also create issues when it comes into contact with permafrost.

Increased precipitation, whether it is snow or rain, increases the vulnerability of bridges and roads. For the transportation industry as well as mine access, increased rain and snow events can lead to issues with culverts that are under-designed and end up washing out parts of the road. This results in increased maintenance costs including replacing culverts. Design for bridge bases and culverts are based on projected river discharges and flow, and depend on accurate precipitation projections.

Increased amounts of snow disrupts traffic, blowing snow in particular affects visibility and can cause major interruptions in the transportation industry. Blowing snow can also significantly increase mining costs because of transportation delays, the inability to bring staff and equipment in and out of the mine, or to move product out of the mine. These delays impact the mine's schedule and profitability. Avalanches were listed as a concern in some areas, although not a common occurrence in any of the regions where the respondents operate. Avalanches can impact access, and blasting may be required around roads, which means bringing in specialists and increasing costs further.

High snow years sometimes result in increased snow build-up on ice, which slows the formation of ice roads. These roads play an important role in ground transportation in the Northwest Territories and late formation of ice roads results in construction delays. Operations may have to delay work or fly in equipment at an increased cost. All weather roads are not necessarily a suitable replacement, as they are expensive to build and maintain, in particular in permafrost environments. Finding materials to build all weather roads can be very difficult in the North. This is a challenge that is arising in the construction of the highway from Inuvik to Tuktoyaktuk. Nevertheless, some operators that are building their own access roads with shorter life spans are turning to all weather roads and permanent bridges as a means of improving access to compensate for warmer temperatures.

Freeze-thaw cycling is another hazard that can speed up road deterioration, leading to increased maintenance and costs. Increased freeze-thaw cycling can also cause damage to infrastructure and equipment, for example, it puts strain on pipe connections, and can increase safety concerns at the work site.

4.2.2. Current Practices

The mining and transportation sectors are actively working to adapt to climate change and deal with permafrost and snow-related challenges in a variety of ways. Some common practices were mentioned in the previous section in relation to specific hazards. There are other common practices that relate to multiple hazards or general operations including using climate data and projections, test studies, and guidelines. Respondents talked about best practices and the struggle to maintain a balance between planning for climate change and economic viability.

There were some commonalities in the data that respondents are using across both sectors. All respondents are currently accessing some climate data that they use in their work, regardless of whether they are involved in the mining or transportation industry. All of the respondents said they use the climate and weather data available on the Environment Canada website, some also use data provided by Yukon government (YG) or Government of Northwest Territories (GNWT) or other publicly available weather stations. Most mines have several on-site weather stations that they and their consultants use to obtain local and baseline climate data.

The data that is consistently used by almost all of the respondents includes temperature, precipitation, wind, and snow depth. Most are also using historical climate data from Environment Canada's climate records including air temperature, seasonal and annual changes, monthly changes in snow precipitation and wind. Some are using Environment Canada's climate normals and noted that they have not been updated since 2000. More than one respondent is manually downloading recent climate information and plotting it to find a new average and rate of change.

Climate trends that are used for infrastructure and mine design are based on best available data so respondents were concerned that the data used would not be appropriate for long-term impacts. When data is not accessible, respondents make conservative assumptions, rely on expertise, or use data from a similar area. Several respondents have used climate data for a larger area or from a somewhat distant weather station in order to interpolate data at a local scale for their sites. There were associated concerns mentioned with spatial resolution and interpolation. Respondents were also concerned with the accuracy of making projections based on historical data and using these projections in planning. One example provided was the commonly used and potentially inaccurate practice of basing new infrastructure design on the warmest year in the past 10 years.

Some of the respondents have used climate change model projections, more so in the transportation industry for highways planning, but also for mining infrastructure, and in particular for tailings facilities. Some respondents questioned their reliability, while others expressed a desire for more information around projections and standardization or guidance as to which projections and GCMs should be used. One respondent uses projections to design tailings by establishing a range of applicable projections using multiple scenarios and adopting models that have successfully predicted current weather patterns. They base their design on the more likely case but keep contingency measures open for a worst case scenario. The respondent's method is to "think about the worst case, but don't design for it because of the uncertainty".

The governments of Yukon, the Northwest Territories, Alaska, China, and other jurisdictions are experimenting with highway road test sections. Currently, monitoring is ongoing on test sections in the Northwest Territories and Yukon including portions of Highway 3 (Northwest Territories), the Alaska Highway in Yukon, and the highway between Inuvik and Tuktoyaktuk. These tests include monitoring new technologies, and monitoring sub-surface temperatures and soil movement. While several respondents mentioned that these tests are extremely beneficial, two also noted that these types of tests take a long time to establish. GNWT is also experimenting with runway stabilizer and other methods to improve airport runways in permafrost-rich terrain.

One respondent that works with both the transportation and mining sectors suggested that changing building codes or best practices for infrastructure might be necessary. One solution is to accommodate permafrost with design parameters, digging deeper than the permafrost to put in supports, changing the foundation or pile design, finding bedrock when possible, avoiding areas with standing water and creating effective drainage. For roads this may mean re-routing them if possible, however in some areas it is impossible to avoid permafrost. The challenge for road design is that roads can cover large distances over highly variable terrain.

Many of the respondents mentioned products with permafrost guidelines, including those produced by the Transportation Association of Canada and the Canadian Standards Association. Respondents from the transportation sector and those working as engineering consultants suggested that these are widely used and generally accepted as best practices. The Transportation Association of Canada has guidelines on building and maintaining roads in permafrost-rich areas. Transport Canada has also delivered guidelines related to permafrost in terms of runway surfaces and bump, as well as snow and visibility guidelines. They are starting to address climate change issues in these guidelines. The Canadian Standards Association is addressing climate change in some of their standards and is developing northern building standards that take permafrost and snow loads into consideration. There have been other guidelines produced in the past in permafrost regions addressing the development of infrastructure. These provided guidance in the form of case studies, and one respondent who found these 'real-world examples' particularly helpful, expressed an interest in seeing those updated and include the tracking of permafrost degradation.

Respondents noted that one of the challenges with these guidelines is that they focus on a single element but do not take into consideration all aspects of ground conditions or how different elements may interact with one another. For example, a guideline that measures rain and how that impacts buildings, does not take into account the impact that rain has on the ground itself and surrounding permafrost.

Many of the respondents noted the challenges of identifying where permafrost exists. There is a need to drill boreholes to understand where ground ice exists and to get a better understanding of the thaw sensitivity. This increases understanding of how the ground in a particular area will react to warming and assists with making decisions regarding permafrost preservation. Some of the respondents are using an active layer and ground temperature thresholds for design decisions.

Almost all of the respondents discussed the difficulty of balancing the costs of design with the risks involved with permafrost. Concern was expressed that over-designing infrastructure could be costly and unnecessary, while under-designing could result in increased maintenance costs. Respondents who act as consultants discussed the challenge of convincing clients that increased costs involved in building better designs can be better economic choices in the long term, in particular with clients that have little experience working in the North. Several respondents identified the need to plan for maintenance by putting aside the necessary funds in preparation for potential long-term settlement due to permafrost thaw and degradation.

4.2.3. Knowledge Gaps

Several respondents expressed a desire to have access to more weather data that is in a more usable format. They would like to have access to more long-term weather stations and use more localized data. The general consensus was that the North is a data-sparse region with too much regional variability in the existing coverage and that it would benefit from more weather stations. While there are some smaller weather stations operated by industry or other groups, most do not provide all the data that is required to calculate ground energy balance or other necessary functions, and many have sporadic data that has not been consistently collected. Examples of data that respondents are interested in accessing are temperature, albedo, cloud cover, wind speed and snow depth. They are also interested in receiving the data in a format that is useable, i.e., available online and downloadable into Excel spreadsheets so they could complete their own analyses and create their own graphs.

Most respondents identified spatial resolution as an issue. They are often dealing with indirect data, or applying data from a larger or different area, and applying that to a smaller, more localized area. One respondent felt that spatial resolution of data poses more of a challenge than availability of data. Local climate stations can provide more information on how snow has changed, or local temperature trends, however often those stations have only been there for a short amount of time so there is no long term data on trends.

Respondents expressed a need for sector-specific guidelines that would indicate which climate data, climate models and projections are most applicable for their area. They also expressed concern that using the wrong data might lead to under-designing infrastructure, while using unrealistic scenarios may lead to a project that is not economically viable. Climate guidelines would also assist with standardizing designs in the industry.

Several respondents indicated that they would appreciate clear guidelines for incorporating climate change considerations, in particular when dealing with assessments, water license applications, or regulatory boards such as the Yukon Socio-Economic Assessment Board. One respondent said that the assessment process lacked clarity and that “dealing with climate change can be as easy as writing a couple of sentences about why climate change is not a factor for the project due to the planned life of the mine”. Several respondents said that currently operators and regulators lack consistency, and that guidelines for climate-change assessments would be helpful.

While some felt that climate change, climate data or assessment guidelines would be good for unifying and creating a standard across the industry, at least one felt that there is too much variability amongst sites and projects to have guides and standards. Several respondents said that climate data changes so quickly that published guides quickly become obsolete.

Respondents involved in both transportation and mining operations identified the lack of seasonal weather forecasting as a major inconvenience. There was also an identified need for better short-term weather forecasts. Improved forecasting would directly affect the profitability of operations through better planning and scheduling. Respondents also said it would be useful to have better estimates of maximum snowfall and snowfall variability. This affects planning for mining operations (e.g., leach operations and mine tailings) and directly affects profitability. Along with seasonal forecasting, respondents identified a need for data and methods that assist with predicting the intensity, frequency and timing of storms.

Clients and companies are not always on the same page with understanding climate projections or designing for climate change. Several respondents said that training or easily accessible educational material would be beneficial to get everyone on the same page and to ensure that they have the same level of understanding. This could be useful in helping consultants explain why more expensive choices are necessary or beneficial. More training on climate projections and the use of climate-change models could be useful for standardizing how people use climate data and data analysis. Generally, respondents are interested in knowing more about the training and other products and tools that are available.

Respondents identified research gaps in the understanding of how ground conditions are affected by different climate parameters, and how those parameters interact. They were interested in being able to predict how the active layer will change with time, and how other changes like ground disturbance (i.e., removal of vegetation) will impact active layer thickness. Respondents working for mining operations said that they are looking for research that they can cite in their regulatory applications.

One respondent felt that there is a need for research that compares the state of practice in the industry with what is being documented by the industry experts in studies such as this one. There is a potential gap between accepted industry best practices and what is commonly being done in the field. The respondent indicated that corporate knowledge is often not retained when experts retire or take their career elsewhere, and many people start their career in the North and then move to another area, taking their expertise with them.

4.2.4. Recommendations

There were some general recommendations that arose from the interviews that informed the development of potential knowledge products. There were clear indications that meteorological data coverage is insufficient in the North. It was recommended that retired climate stations be re-established. It was also recommended that additional variables be recorded at more climate stations, such as those required for surface energy balance calculations for permafrost modelling, like irradiation and evapotranspiration.

The general preference of most of the respondents was to have products available online, although a couple of respondents preferred using printed publications. Generally it was recommended to provide as much information via the internet as possible. Most practitioners used the internet as their main source of information. One practitioner raised concerns that printed guides and standards may not cycle rapidly enough to address climate data needs in the North, and this could potentially be improved by hosting them on the internet and updating them on a regular basis.

Furthermore, interview respondents indicated a need for more robust infrastructure. Several respondents mentioned issues related to repeated loss of internet service, which is a concern when the internet is the main source of information.

5. KNOWLEDGE PRODUCTS

The two knowledge products developed as part of this project – i) the Climate and Infrastructure Forensic Analysis System (CIFAS) and ii) CIFAS case studies and automated reports – were produced to fill the knowledge gaps regarding permafrost, snow hazards, and related adaptations that were identified through the literature review and interviews with industry practitioners. Interviewed practitioners identified the need for more information on both engineering successes and failures, and identified this as integral to improving current practices.

The product concepts were developed from interviews with industry practitioners and an in-depth literature review focused on permafrost and snow, and the mining and transportation sectors. Following completion of interviews and the literature review, information was synthesized into identified needs or knowledge gaps, and the potential knowledge products that could fill those gaps. The list of potential knowledge products was shared with the Project Advisory Committee and other interested practitioners, who then provided recommendations and feedback. The result was that these two products were identified both as valuable for the transportation and mining sectors, and as viable for the scope of the project. Through targeted consultation with industry practitioners, decision makers and government representatives, the products were further refined to be as relevant and as useful as possible.

5.1. Product Development

The products were developed through an iterative process beginning with the development of a draft database structure. The Project Team located as much information as possible on cases of impacts to northern ground transportation services and infrastructure and developed the database fields using that information and feedback from the Project Advisory Committee (PAC), Project Team members, and product dissemination partners. The Project Team populated the early draft database structure by evaluating literature-review materials, practitioner interviewee responses, and other documents collected or developed during the early phases of the project.

Further information on specific cases of impacts to northern transportation infrastructure and services, as well as successful adaptations, were identified by conducting online searches for technical reports, news reports, and press releases. Working with the PAC and dissemination partners, and interviewing practitioners associated with specific impact events added more details to fill out the event listings. The Project Team identified climate change-specific vulnerabilities, including commentary on expected future challenges and relevant adaptation strategies for each individual listing. Throughout this process, the online database structure was refined as necessary. Two locations for in-depth case studies of infrastructure failure were identified and information was gathered on those case studies. A further analysis was completed to identify elements that led to the failure.

5.1.1. *PRODUCT OBJECTIVES*

CIFAS and the two case studies were developed in accordance with the following objectives:

- focus on providing the climate-, cryosphere-, and infrastructure-related information most required by practitioners involved in planning, designing, constructing, maintaining and operating northern ground transportation networks;
- focus on the Yukon and NWT, and permafrost- and snow-related impacts and adaptation measures (as per the original project plan), with an option to include equivalent information for Nunavut and other cryosphere elements in the future;
- provide easy on-line access to government departments, codes and standards organizations, transportation service providers, research institutions, and other key user groups;
- allow for future expansion of the database to include information on a wider range of northern sectors and climate change-related hazard types; and,
- aim to serve as a definitive source of information for use in evidence-based adaptation decision making.

5.2. RATIONALE FOR THE KNOWLEDGE PRODUCTS

These products are required in order to:

- support pan-northern and regional assessments of changing maintenance requirements for northern ground transportation infrastructure;
- support local and regional transportation planning, and the provision of adequate navigational assistance and emergency management services;
- establish the evidence base required in order to renew existing, as well as develop new codes, standards, and related instruments for the planning and design of northern ground transportation infrastructure; and,
- build the evidence base to support improved infrastructure in northern environments, to track infrastructure challenges, and to improve planning and budgeting for infrastructure maintenance.

5.2.1. *INTERVIEW AND LITERATURE REVIEW RESULTS*

The majority of interviewees from the northern ground transportation sector provided examples of infrastructure failures and/or major service interruptions for which snow, permafrost, and the impacts of climate change were cited as main contributing factors.

These interview results are consistent with findings from the literature review completed for this project, which also suggest that important knowledge gaps currently exist in adaptation related to the impacts of climate change on snow- and permafrost-related hazards and northern ground transportation. The main hazards are described as follows:

- more frequent and severe permafrost-induced slumping;
- more pronounced permafrost-induced subsidence;
- more frequent rain on snow events, precipitous spring freshet, and related flooding (Rawlings et al., 2009; TAC, 2010);

- deeper and heavier extreme snowfall events, and larger total amounts of snow over a shorter snow season(Pearce et al., 2009; GNWT, 2004a; McGregor et al., 2008; Stephenson et al., 2011; TAC, 2010); and
- changes to the winter-road season(Pearce et al., 2009; Rawlings, 2009; Stephenson et al., 2011; TAC, 2010).

Transportation infrastructure failures may be due to unforeseen or previously ignored or misunderstood factors. For example, newly constructed sections of Highway 3 in the NWT, designed using climate change adaptation strategies that were aimed at preserving permafrost (McGregor et al., 2008), have recently experienced failures likely associated with meltwater (Project Interview Results). The adaptation strategies used were based on the assumption that warming air temperatures would have the greatest impact on permafrost conditions beneath the road; however, the impacts of surface and near-surface water budgets (heavily influenced by snow melt and seasonal water storage) may deserve much more attention than previously thought, particularly under warm permafrost conditions.

Changing snow and permafrost conditions in the North have been documented through peer-reviewed literature (UNEP, 2012; Osterkamp, 2003; Romanovsky et al., 2010; Joe-Strack and Janowicz, 2009a-c), recent federal and territorial (GNWT, 2004a) government initiatives, as well as the broader research community (Hennessey et al., 2011; NCE, 2011a,b).

Several interviewees noted that real-world examples of failures and/or adaptation design measures provided in some guidance documents and design guides were among the most useful to inform their transportation infrastructure planning, design and operation decisions. The literature (e.g., Stephenson et al., 2011; Pearce et al., 2009) also suggests a need for the sharing of these examples through case studies, including quasi-forensic analyses of the impacts, and the nature of the events.

A number of literature sources (e.g., Pearce et al., 2009) indicate the need for more climate and climate change impacts and adaptation assessments for northern infrastructure. Several cases discovered during the literature review process provided specific examples of northern Canadian ground transportation infrastructure failures. These serve as both an indication of climatic design adaptation gaps, as well as a basis for populating the proposed forensic tool.

Online resource databases to inform climate change adaptation go beyond providing a location for users to find information to support climate-sensitive decision making – they encourage increased awareness and attention to climate-change impacts and, if designed well, can foster interaction between experts that will encourage the growth of the field of study. Similar impacts databases have been developed previously for southern regions of Canada by Project Team members. Their experience with these databases provides both insight and qualification for generating the proposed product.

Finally, impacts databases are a critical means for the development of an evidence-base required by codes and standards committees in order to help justify changes in design, maintenance and/or operational guidelines, and standards.

5.3. Climate and Infrastructure Forensic Analysis System (CIFAS)

The main product is a forensic analysis system of snow- and permafrost-related impacts to ground transportation and mine-access roads in the Canadian North, focusing mainly on Yukon and the Northwest Territories. It was designed with the potential to expand at a later date to include other types of infrastructure such as pipelines, buildings, etc. It is designed to be easy to use, web-accessible, easily support data entry, queries and other database functions, and have the ability to generate reports, tables and figures.

CIFAS allows for the storage, management and basic analysis of the following information:

- type, location, age, and ownership of ground transportation infrastructure(s) impacted by snow- and permafrost-related hazards;
- type, location, and jurisdiction of ground transportation services impacted by snow- and permafrost-related hazards;
- character (e.g., timing, duration and magnitude) of the permafrost- or snow-related event(s) resulting in each reported impact(s);
- character (e.g., timing, extent and magnitude) of each reported impact (to service levels or infrastructure conditions) resulting from the permafrost- or snow-related event(s);
- primary vulnerability characteristics (e.g., particular engineering-related sensitivities) affecting the timing, extent and magnitude of the service- or infrastructure-related impact;
- potential significance of climate change for all of the above;
- design or management guidance available with respect to the impacted service or infrastructure;
- design or management protocols used with respect to the impacted service or infrastructure;
- climate and other environmental information used with respect to the impacted service or infrastructure (i.e., design assumptions);
- adaptation options and cases of successes of potential relevance to each reported impact; and,
- sources of planning, design, or operational guidance related to the impacted assets or services, including relevant design codes and standards.

The importance of forensic investigations and the application of their findings were made clear by both the interviews and literature review components of the project. This is also consistent with climate change adaptation literature in general regarding the utility of post-event or post-failure analysis. While the current project relates specifically to mining and northern surface transportation, the methods and applications described below can fundamentally be applied far beyond these topics, delving into most other forms of engineering, emergency response, and operations and management relating to other natural hazards and their impacts.

The main page of the Climate and Infrastructure Forensic Analysis System uses Google maps.

5.3.1. Uses of Climate and Infrastructure Forensic Analysis System and Case Studies

Information that helps decision-makers to understand their current vulnerability to high-impact weather and climate events can provide a powerful catalyst for further awareness and actions to reduce current and future vulnerabilities (Breysse, 2013; De Groeve et al., 2013). It is this form of analysis that provides the foundation for adaptation to current and future climate hazards by identifying needed actions.

Forensic analyses can be used to track trends in impacts and their costs, to highlight regions of higher vulnerabilities to specific cryosphere hazards, and to guide the current planning of risk-reduction strategies and into the future (ICSU, 2013). The CIFAS information can be used to identify lessons learned from a series of events, can yield insights into the return periods of high-impact climate events, and can identify infrastructure types and practices at greatest vulnerability. The system also has the potential to highlight priority changes needed for infrastructure codes, standards, and disaster-risk reduction measures. The combination of the forensic analysis with guidance on climate event trends and future projections presents an opportunity for sectors to develop adaptation responses that reduce northern infrastructure risks and losses today, and into the future.

5.3.2. Infrastructure Failures and Underperformance

The CIFAS system addresses both infrastructure failure and underperformance. Collapse and structural failures can occur due to material properties or overloading when the load, such as the weight of snowpack, has more severe effects than the structure or its materials were designed to bear. Sometimes, the capacity of a structure can decline due to weathering or deterioration with time or lack of regular maintenance. Human factors at any stage (design, building or service) can also contribute to failure through under-design, changes in design requirements over time, insufficient knowledge, risks that were conscientiously considered to be low, or communication problems (UNDP, 2013).

Underperformance refers to a reduction in service levels in which infrastructure does not fail or break in a structural sense, but also does not achieve performance objectives. Examples of such events from the CIFAS system include weight restrictions placed on roads due to wet ground conditions and increases in traffic volume (e.g., sections of Hwy 3 near Deh Cho Bridge, NT, May 2013), and increases in traffic collisions due to poor road surface conditions (e.g., Hwy 3 between Fort Providence and Rae Edzo, NT, January 2005). While service is still available, infrastructure is performing below design capacity due to environmental loading, and costs from these types of incidents, though more difficult to quantify, can accumulate quickly.

Changing cryosphere conditions in the North – including decreasing length of snow cover season, shorter ice-road seasons, increasing extreme snow depths and weights, more rain on snow events, increasing extreme snowmelt events, and changing permafrost conditions – are all producing significant impacts on mining and transportation infrastructure. The case studies outlined in CIFAS all illustrate the vulnerability of existing transportation and mining infrastructure to changing cryosphere conditions in the Yukon and Northwest Territories.

5.3.3. Critical Thresholds for Adaptation Actions

Nearly all infrastructure currently in service have been designed assuming past climate conditions and will represent conditions expected over the future lifespan of the structure. For example, the climatic design values used in codes, standards and guidelines for design of reliable and economical infrastructure include quantities such as the 10-, 50- or 100-year return period ‘worst storm’ rainfall or snow conditions and are typically derived from historical climate data. The assumption that the past represents the future has worked well until recently but is no longer holding well, particularly in northern regions where the climate is changing rapidly.

Forensic analyses often reveal that infrastructure failures result when weather and climate extremes approach or exceed the structure’s historical design values (Auld et al., 2010). Often, forensic studies show that, above critical climate thresholds, small increases in weather and climate extremes can have the potential to bring on large increases in damage to existing infrastructure. For example, previous Environment Canada studies (Auld, 2008a,b) indicated that damage to infrastructure from extreme weather events tends to increase dramatically above critical thresholds, even though the storm events associated with these damages may not be much more severe than the type of storm intensity that occurs regularly each year (Munich Re, 1997; Swiss Re, 1997; Freeman and Warner, 2001; Coleman, 2002; Auld, 2008a,b). In many cases, it is likely that these critical thresholds reflect storm intensities that exceed the historical design conditions for structures that were built earlier to lower capacities or loads. The lower climate loads used for design in the past may have reflected lower extremes in the past climate record, insufficient or limited climate information (e.g., short data records that did not capture the full range of extremes), or poor quality climate data.

In order to carry out useful forensic analyses of infrastructure failures and to have useful guidance for future design practices, there is a need for good documentation on failure and underperformance events, including an estimate of the original design, construction and maintenance information, as well as good documentation on the failure conditions. The CIFAS system includes a database with documentation on the state of the infrastructure, its failure conditions, climate conditions likely contributing to the failure, and a user-friendly interface that facilitates searches and statistical analyses of the failure event.

5.3.4. Engineering Considerations

Nearly all failures are due to a combination of both human and environmental (in this case climatic) factors, and hence information on design, maintenance, and material properties are as significant as measures of climatic loading. Factors such as poor maintenance or periods of abandonment, material weathering or fatigue, poor or flawed construction, or simply overuse of infrastructure beyond its design life, may have also contributed to a specific failure or underperformance incident. Age and fatigue, for example, have already been implicated in a number of cases currently held in the CIFAS system (e.g., large culvert collapse Dempster Hwy at Caribou Creek, YT, September 20, 2007). As such, relevant data on these factors should also be collected and evaluated in combination with climate and weather contributions. There are numerous infrastructure components that are sensitive to climate. Reports similar to the second knowledge product can help identify what those components are and which design elements were at fault in the infrastructure failure.

Determining the contribution of engineering design (Hales, 1998) and materials (Lewis et al., 2003) to infrastructure failure and underperformance requires information containing descriptions of failure characteristics, including on-site visual information, verbal, and/or written accounts. This information can provide a failure sequence and can help differentiate between event-related damage and pre-existing damage from potential flaws in engineering or materials. The ultimate purpose of analysing this information is to determine how the component(s) failed, when they failed, and in what order. These are then related to both the history of the piece of infrastructure, as well as its interaction with environmental and other loading.

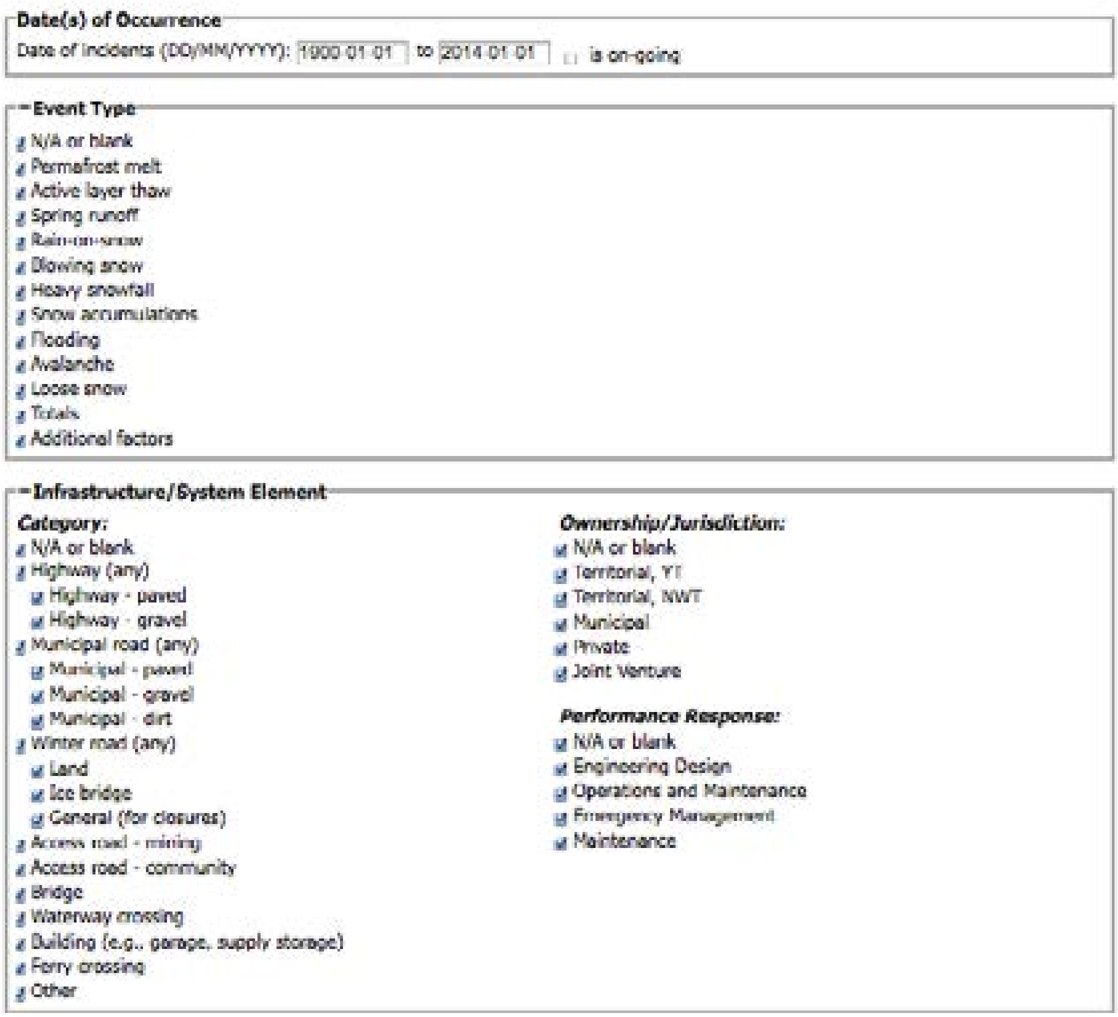
5.3.5. Types of Cryosphere Forensic Events

Snow and ice-related events can cover all time scales and can range from sudden onset impacts to longer term, sometimes multi-year or multi-decadal processes; CIFAS failure and underperformance cases attributed to changing cryosphere conditions represent the full range of event types. Some are short-lived or intense weather events such as extreme blizzards and heavy snowfalls, while others represent seasonal events such as heavy buildups of winter snowpacks, spring rainfall combined with rapid snowmelt, and abnormally short ice-road seasons. Additionally, other events represent long-term processes, such as changing permafrost conditions and weathering of materials. These events are often inter-connected, where one high-impact cryosphere event can trigger another, such as a significant spring rainfall in conjunction with rapid snowmelt (mentioned above), or an ice jam on a river resulting from rapid warming and increased runoff.

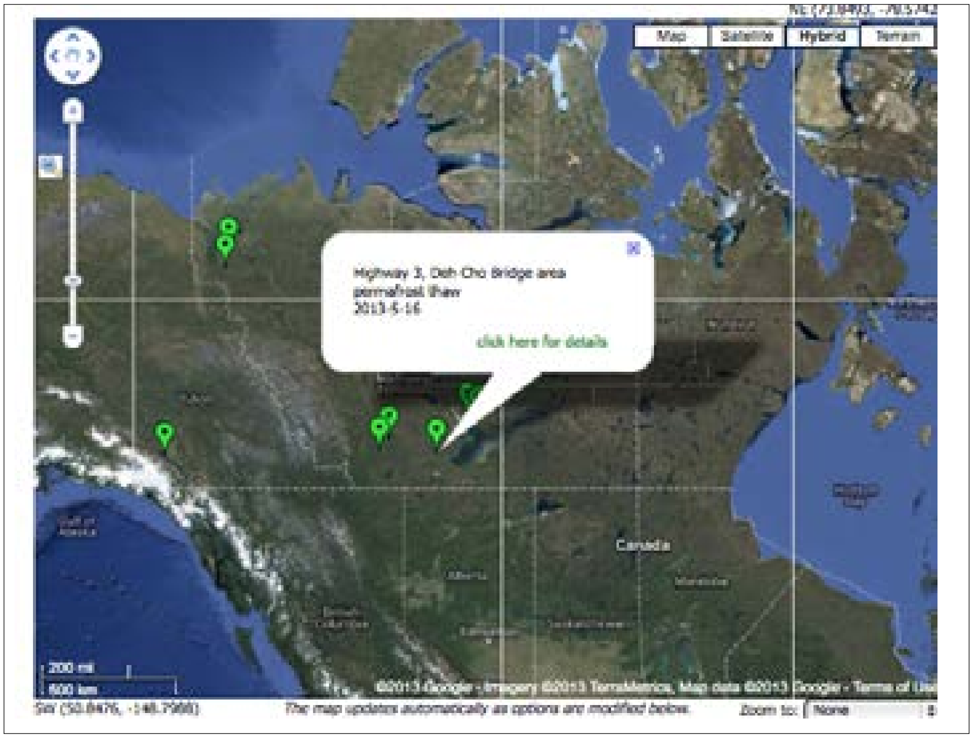
The events in CIFAS cover a variety of time scales and can be roughly categorized as:

- short-term emergencies: blizzards, heavy snowfall events
- seasonal creeping events: heavy winter snowpacks, rapid spring snowmelt leading to increased runoff and flooding, abnormally short or disastrous ice-road season

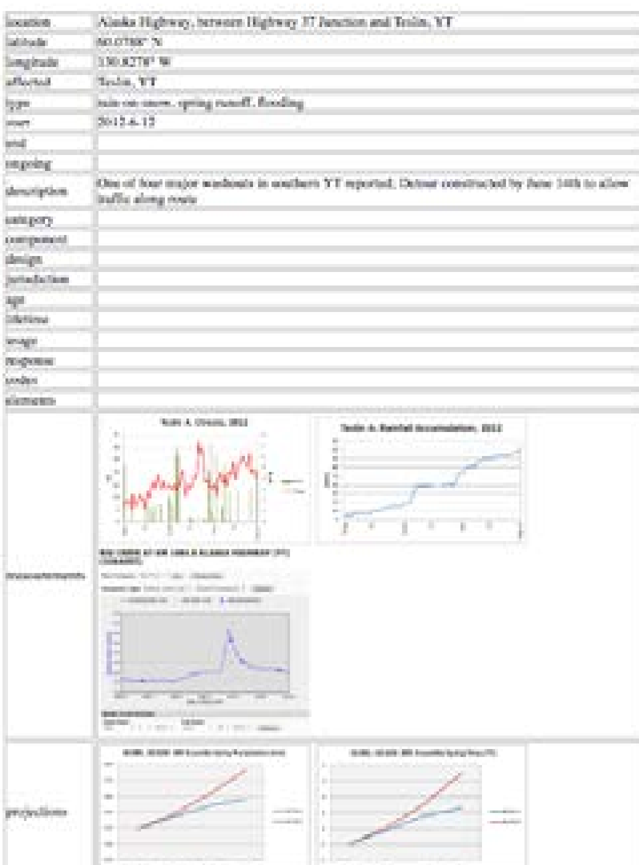
- combination events: significant spring rainfall combined with rapid melt from a heavy snowpack, ice-jam flooding
- long-term, multi-year onset events: permafrost thaw and thickening of the active layer



CIFAS allows users to search by event type or infrastructure/system element and narrow the field by dates of occurrence.



A search will narrow the field and provide an information bubble with basic details.



location	Alaska Highway, between Highway 37 Junction and Teslin, YT
latitude	60.0788° N
longitude	130.8278° W
affected	Teslin, YT
type	rain on snow, spring runoff, flooding
start	2012-6-15
end	
ongoing	
description	One of four major washouts in southern YT reported. Detour constructed by June 14th to allow traffic along route
category	
component	
design	
jurisdiction	
age	
lifetime	
image	
response	
codes	
elements	
measurements	
projections	

For each incident the system can generate a form with available information, including climate trends and projections, if available.

5.4. Case Studies and Automated Reports

This second product is a derivative of the *Climate and Infrastructure Forensic Analysis System* and provides descriptions and examples of the utility of the ultimate outputs from the CIFAS system. The case studies are an example of the type of report that could be developed through the use of CIFAS. Ideally, a simpler version of this type of case study could be produced by CIFAS as an automated report, with recommendations on how to use the available information and data to conduct a more in-depth case study. This product description includes the format, assessment methodology, results application, and two sample case studies with analyses.

The case studies provided in Appendix D represent two related combination or 'complex' events from 2012 involving heavy snowpacks, rapid spring warming and significant spring rainfalls leading to disastrous flooding, infrastructure failure and emergency responses. Both mining and transportation infrastructure were impacted by these two events in both the Yukon and the Northwest Territories.

They were chosen from the infrastructure hazards identified in populating the database and were then subject to a more in-depth study of the identified hazards, the particular climate and weather information and more localized data. The analysis included a study of the interplay or relationships between these variables, and of the elements that led to the infrastructure failure.

5.4.1. Automated Reports

The product described here consists of automated reports that provide the basis for the interdisciplinary forensic analysis of the type described above. Automated reports would first be generated using fields held in CIFAS. Two types of formats are envisioned, those for *single incident* or *single asset case studies*, and those for *cross-incident* forensic analyses. The former focuses on an individual event and/or piece of infrastructure, while the latter refers to either multiple incidents or pieces of infrastructure grouped together by one or more common characteristics, such as geographical region, infrastructure element type (e.g., access road, culvert, municipal road) or climate/meteorological driver (e.g., rain-on-snow event, active layer thaw).

Main headings for *Single Incident/Asset Reports* include the following:

1. Incident Overview
2. Overview of Affected Infrastructure
3. Atmospheric Hazard Event
4. Engineering Considerations
5. Response to Event
6. Forensic Analysis
7. Climate Trends, Projections and Future Risks
8. Adaptations and Recommendations

Detailed descriptions and sample content for these headings are provided in the case studies in Appendix E. Note that "Forensic Analysis" is placed before "Future Risks" since causes (or at least possible causes) should be identified in preceding report sections before applicable climate-change projections can be identified and used. Sections and headings will contain all respective information available in the original CIFAS listing, highlighting areas where data is missing. The automated report can then be copied into a document editing platform for further analysis.

In contrast, *Cross-Incident* reports group events by one or more common attributes with the goal of determining commonalities in contributing factors. These would address items such as event frequency, comparison in magnitude of contributing climate and weather factors and indices for similar events, identification of regional sensitivities, determination of climate 'breaking point' thresholds, and so on (outlines for Cross-Indent Reports have not been developed here). The potential forms and uses of cross-incident studies are numerous and merit further development.

5.4.2. Forensic Guidance

Forensic analysis requires the application of objective and critical thought beyond the raw data that is provided, and it is therefore impossible to conduct a full forensic assessment in an automated fashion. As indicated above, automated reports will therefore provide additional forensic guidance to assist users with analyses of climate and infrastructure information (see bolded blue text in the case studies in Appendix D). In addition to this, a number of example case studies would be provided on the CIFAS system for users to review completed cases. Several references from the grey and peer-reviewed literature will also be noted to provide additional case study examples as well as refinement of analysis techniques and discussion (future work may include the compilation of case studies relevant to the system, e.g., McGregor et al., 2008).

Forensic guidance will include a series of questions which can be used to interrogate and combine the climate and engineering data to assist the user with determining the causes and contributing factors for the failure or underperformance event. This may include identifying and documenting available and needed data relating to the incident, up to, and including, consideration of the design process itself and its stages (Hales, 1998) which may have contributed to vulnerabilities and, ultimately, failure.

A few additional references which help describe the forensic analysis process are provided here. While much forensic engineering literature focuses on investigation and analysis within the context of legal proceedings (e.g., Hales, 1998; Noon, 2000; Lewis et al., 2003), reasoning and processes discussed within these references are still directly applicable. Weather and climate-related failures have in the past been subject to legal proceedings (Lyons, 2004); however, those who will potentially act as expert witnesses should seek proper advice from both a legal counsel, as well as experienced forensic engineers.

5.4.3. Automated Components and Figures

While full automation of a forensic report is not possible, automation of specific figures and components is. The following figures could be developed in an automated fashion and generated for specific reports, either case-specific or cross-event fashion:

- mapping data source locations relative to incident or incidents (e.g., Fig. 3 in Case Study 1);
- graphing antecedent temperatures, precipitation amounts and accumulations for comparison with historical values or climatic averages over relevant time periods (e.g., days preceding a flood event or years to decades preceding a permafrost-related failure); and
- graphing timelines depicting maintenance history (long term, years) or sequence of events (short term, hours), possibly combined with climate and weather data.

These and other figures and visualizations could be generated in an automated fashion and will assist users in their forensic analysis. As the CIFAS system is developed further and more case studies are executed, commonly used figures will continue to be identified and added to the suite of automated capabilities of the system.

5.4.4. Developing Climate Change Adaptation Solutions

The ultimate goal of these forensic analyses is to provide fact-based adaptation solutions to reduce the risks of similar failures occurring in the future. Benefits include the following:

- Fact- based input for guides, codes and standards by highlighting design needs identified by failures;
- new design values due to changes in climatic loads, determining sensitive design elements which can be addressed by future maintenance or new design clauses, or by identifying climate and weather breaking-point thresholds which should be monitored;
- information for disaster response and management, including needs for improved communication or modification to protocols;
- indications of needed changes or improvements in weather and climate forecasts for organizations when designing specific pieces of infrastructure;
- identification of effective climate change adaption measures, through comparison to other case studies through literature, cross-incident analysis, or case-specific examples of effective measures; and
- the development and coordination of longterm monitoring and assessment of both infrastructure assets and of important climate and weather elements.

These and other benefits are the ultimate goals of forensic analyses, and the CIFAS system is designed to facilitate and direct this complex process to the greatest extent possible. These benefits can only be achieved, however, when embedded within a larger, integrated adaptation platform that puts adaptation recommendations into action.

6. DISSEMINATION STRATEGY

The dissemination strategy was developed simultaneously with the knowledge products to ensure the knowledge products were created with the inclusion of input and feedback from the target audience, and also to ensure that the final products reach user groups.

6.1. Target Audience

The target audience for these products includes industry practitioners working in the mining and transportation sectors in northern Canada, government departments, and professional associations related to engineering, mining and transportation. The target audience also includes associations producing standards, guidelines and best practices related to the mining and transportation sectors. The practitioners targeted by the products include engineers, government decision-makers in departments of transportation and mining, industry professionals, professional engineering associations, standards associations, mining associations, and regulatory bodies. Anyone who is involved in the planning, operations, remediation, and regulation of transportation and mining, or is involved in creating standards or design guidelines for these sectors is included in the target audience for these two products. More specifically, the target audience includes:

- professional associations: Engineers Canada, northern engineering associations (e.g., Association of Professional Engineers of Yukon, NWT and Nunavut Association of Professional Engineers and Geoscientists)
- industry associations: Chamber of Mines

- codes and standards organizations: Canadian Standards Association, Transportation Association of Canada, the Northern Infrastructure Adaptation Initiative
- government departments: Public Works, Transportation, Emergency Management, Economic Development, Land Planning
- municipal and community associations: Federation of Canadian Municipalities, Association of Yukon Communities, NWT Association of Communities
- transportation and mining sector practitioners: surface operation managers, environmental managers
- adaptation organizations: OCCIAR, the Pan-Territorial Adaptation Partnership

6.2. Targeted Engagement in Product Development

The first part of the dissemination plan involved engaging members of the target audience and potential dissemination partners in the development of the products. The goal was to raise awareness around the products and engage potential partners and users in the development of the product to ensure the usefulness and relevance of the product. Frequent interaction with eventual dissemination partners was maintained over the course of the project through refining the product concepts, refining design specifications for the products, and researching cases of infrastructure and service impacts to populate CIFAS.

The Project Team conducted targeted consultations with:

- PAC members (academics from permafrost and snow)
- industry practitioners (geotechnical engineers, mining practitioners)
- professional associations (Engineers Canada)
- government representatives (NRCan, Transport Canada, Government of Yukon, GNWT)
- adaptation practitioners (OCCIAR, Mirarco)

The Project Team also presented on the draft knowledge products at the Transportation Association of Canada conference and via online webinar to solicit discussion and feedback on the products. The products and dissemination strategy was also presented via webinar to NRCan's Northern Working Group to gather more feedback. The presentations were also an opportunity to discuss and get feedback on potential dissemination partners, and possible hosting options for CIFAS.

6.3. Product Sustainability

In the original product proposal the goal of the dissemination strategy was to ensure that the products reach the audience. As the products were developed, it became clear that one of the major challenges would be finding a host for CIFAS and ensuring the sustainability of the products. The goal of the dissemination strategy was expanded to include finding an appropriate host for the online system. This is an ongoing role for the Project Team that will carry on once the project is completed.

When considering potential hosts, the Project Team is considering parties who:

- already play a role in disseminating information relating to northern climate change impacts, natural hazards, northern transportation infrastructure or services;have the capacity and access to the expertise required to maintain CIFAS and update data entries or expand and develop it as needed; and,

- are interested in interacting with key user groups, such as professional and sector associations, and codes and standards-related organizations

A secondary consideration is to identify potential dissemination partners who can either support the system host, share the product with their members, or link to the product. Potential partners can ensure that CIFAS is referenced in key publications (i.e., related codes and standards), and linked to key processes and institutions that can benefit from the system. These potential partners include:

- territorial departments of transportation
- territorial geomatics groups
- territorial professional engineering associations
- territorial planning associations
- territorial business associations (e.g., consulting engineers)
- territorial regulatory bodies (e.g., land and water boards)
- territorial departments and secretariats responsible for CC responses
- Transportation Association of Canada
- Canadian Water Resources Association
- Mining Association of Canada
- Canadian Standards Association

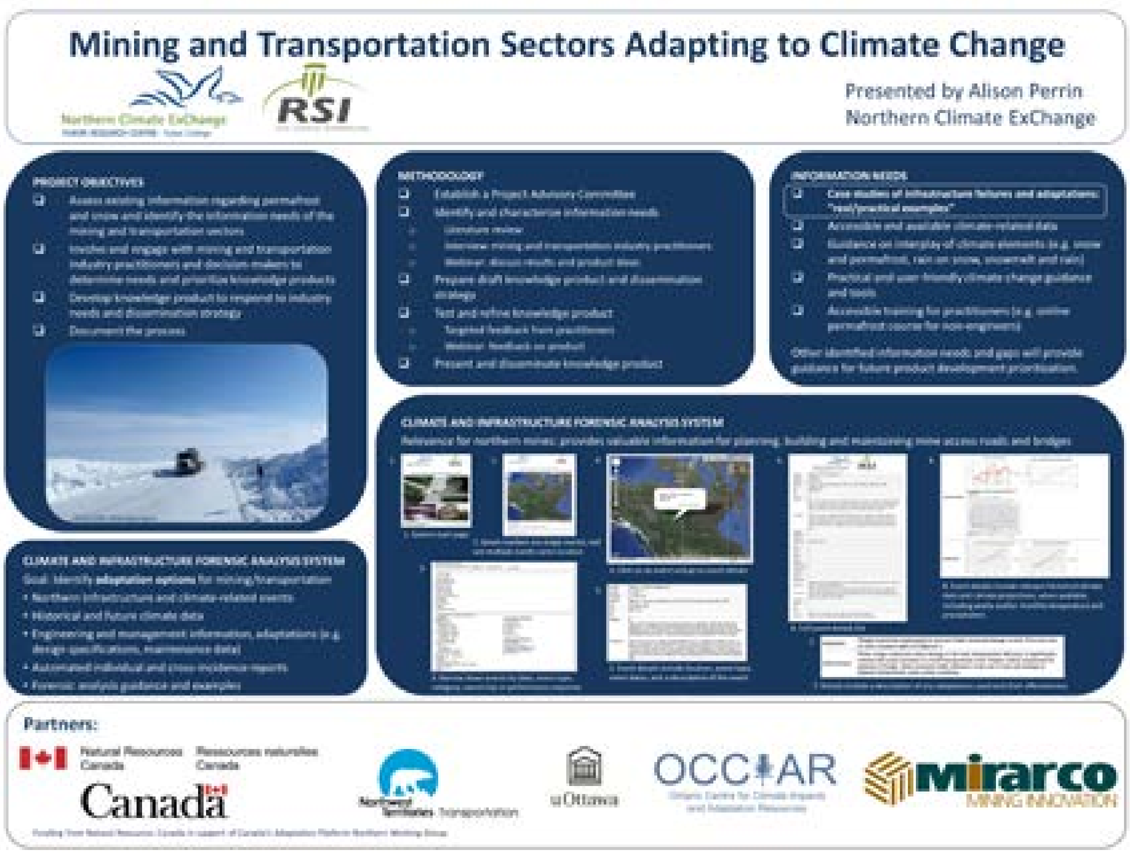
There are three basic models for hosting CIFAS that would make it an effective tool for practitioners.

1. The first option is to have Risk Sciences International (RSI) further develop the system and support its transition into a government department who would become its ultimate host and maintainer. RSI would be prepared to provide assistance bringing staff up-to-speed on the system and assisting with improvements. One of the challenges with this option is the potential for the system to become associated with the host territory and to lose its relevance to other parts of the region.
2. The second option is for Risk Sciences International to further develop the system and support its transition to an organization that could host the system. This could be a professional organization, such as Engineers Canada, a standards association like the Transportation Association of Canada, or a non-profit such as OCCIAR. For these organizations the challenge is to find on-going funding for the system, or the system might become dated and obsolete. Professional or standards organizations may choose to charge for use of the system, which may make it inaccessible for some potential users.
3. The third option is for Risk Sciences International to further develop the system and host it on a protected server with ‘bannering’ or ‘branding’ tailored to one or more northern organizations or governments. RSI, as the current host of the system, could continue to house and maintain the system, while territorial governments and/or other users host the client interface on their webpage. RSI currently hosts, maintains, updates and routinely improves web-based decision support tools for a number of organizations. Depending on the tool, the agency, and the user group, access to the tool can be either public or protected. With this option, there is a way for more than one organization or government to make CIFAS available on their webpage with their branding. The challenge for this option is to find funding to support Risk Sciences International in hosting the system; however, with a multi-jurisdictional approach, cost sharing across

the region could be an option and costs would be minimal with potential options for partners to assist with data entry and updating services.

6.4. PUBLIC DISSEMINATION

Public dissemination of the product is essential for building interest, exploring potential hosting ideas, and to share the products with future users. This phase of dissemination is ongoing and began with attendance at the Pan-territorial Permafrost Conference in Yellowknife in November 2013. Project Team members gave a presentation on the project, knowledge products and dissemination strategy as part of the Transportation session. The presentation was well received and generated conversations with potential user groups around hosting options. The second public presentation was at the Yukon Geoscience Forum in Whitehorse, Yukon in November 2013. A member of the Project Team presented the project as part of the poster session, which provided the opportunity to discuss the project with practitioners on an individual basis. Upcoming steps in dissemination include taking part in the NRCan adaptation webinar series to present final knowledge products.



Poster presented at Yukon Geoscience Forum, November 2013.

7. CONCLUSIONS

While the project has concluded, the dissemination of CIFAS still requires ongoing attention. Finding a sustainable option for maintaining a relevant, accessible and current system will require a coordinated response and a source of funding. The response from the user groups identified in the dissemination strategy has been supportive and encouraging, and many of the participants have shown interest in finding a long-term solution to finding a host for the system. Members of the project team will continue to work with NRCan through the Northern Working Group and the adaptation webinar series to disseminate information on the products and search for a hosting solution.

The methodology was a successful pathway to identifying information gaps and potential products, as well as tailoring products to the practitioners. The literature review provided the base for the entire project by giving Project Team members a broad understanding of the information that is available, how it is being disseminated and who is using it. The interviews and further discussions with practitioners were crucial in determining which information needs were a priority, and how they could be best answered or addressed. Broadening the project scope to include a targeted consultation on top of PAC engagement was particularly useful for tailoring the products, garnering support and minimizing time demands on volunteer advisors.

7.1. Recommendations

One of the goals of this project was to assess and recommend additional courses of action that may be required in order to meet the information needs of the mining and transportation sectors. There were several knowledge gaps and potential products that were identified during this project that are included here as recommendations for future product development.

1. Easily accessible and tailored climate hazard-related data; almost every respondent mentioned the need for more data and some were worried that the data they were using was not appropriate for their area or when evaluating long-term impacts.
2. Guidance on the complex interplay of climate elements such as snow and permafrost, rain on snow, etc.
3. Practical and user-friendly climate-change guidance and tools; some of the respondents said they had difficulty convincing decision-makers to design for changes in snow and permafrost. Better education, best practices, outreach materials, and examples or case studies showing the financial benefits of adaptations were suggested as possible solutions to combat the misunderstandings around adaptation amongst decision-makers.
4. Accessible training for practitioners and decision-makers was suggested as a valuable tool. Practitioners were interested in training that could be accessible by internet or completed remotely at their desk. Possible course topics include permafrost and weather/forecasting training. These courses should be targeted at people working in the industry who are not experts in that area but may be working with experts, or with the data.

8. REFERENCES

Auld, H., 2008a. Adaptation by Design: The Impact of Changing Climate on Infrastructure. Journal of Public Works and Infrastructure, vol. 1, no. 3, p. 276-288.

Auld, H., 2008b. Disaster Risk Reduction under Current and Changing Climate Conditions: Important Roles for the National Meteorological and Hydrological Services. World Meteorological Organization (WMO) Bulletin 57 (2), p. 118-125.

Auld, H., Comer, N. and Fernandez, S., 2010. TECHNICAL GUIDE Infrastructure in permafrost: A guideline for climate change adaptation. Canadian Standards Association (CSA) Special Publication, Chapter 5 (PLUS 4011-10), p. 41-53.

Breysse, D., 2013. Failure case databases for teaching risk in civil engineering. In Fifth International Conference on Forensic Engineering, April 16-17, 2013, London, UK. Accessed December 18, 2013 at: http://www.ice.org.uk/ICE_Web_Portal/media/Events/Failure-case-databases-for-teaching-risk-in-civil-engineering.pdf

Coleman, T., 2002. The Impact of Climate Change on Insurance Against Catastrophes. Insurance Australia Group, Melbourne, Australia, http://stephenschneider.stanford.edu/Publications/PDF_Papers/IAG-Climate_Change_Paper.pdf

De Groeve, T., Poljansek, K. and Ehrlich, D., 2013. Recording Disaster Losses: Recommendations for a European approach. European Commission, Publications Office of the European Union, Luxembourg, http://publications.jrc.ec.europa.eu/repository/handle/111111111/29296

Freeman, P. and Warner K., 2001. Vulnerability of Infrastructure to Climate Variability: How Does This Affect Infrastructure Lending Policies? Report Commissioned by the Disaster Management Facility of The World Bank and the ProVention Consortium, Washington DC, USA, 42 p.

GNWT (Government of the Northwest Territories), 2004. Risk assessment and analysis report: Building roof snow overload. Government of Northwest Territories, Public Works and Services, 9 p.

Hales, C., 1998. Forensic Analysis of the Engineering Design Process. *In:* Designers, E. Frankenberger et al. (eds.), Springer-Verlag London Ltd., p.137-148.

Hennessey, R., Jones, S., Swales, S. and Duerden, F., 2011. Dawson Climate Change Adaptation Plan, Revised Edition. Northern Climate ExChange, Yukon Research Centre, Yukon College, Whitehorse, YT, 64 p.

ICSU (International Council for Science), 2013. Disaster Risk. ICSU Working Group on “Forensic Investigations of Disasters”. Accessed December 18, 2014 at: http://www.icsu.org/what-we-do/interdisciplinary-bodies/irdr/?icsudocid=working-groups

Joe-Strack, J. and Janowicz, J.R., 2009a. Yukon Snow Survey Bulletin and Water Supply Forecast: March 1, 2009. Water Resources Branch, Department of Environment, Government of Yukon, 26 p. http://www.env.gov.yk.ca/air-water-waste/snow_survey.php

Joe-Strack, J. and Janowicz, J.R., 2009b. Yukon Snow Survey Bulletin and Water Supply Forecast: April 1, 2009. Water Resources Branch, Department of Environment, Government of Yukon, 26 p. http://www.env.gov.yk.ca/air-water-waste/snow_survey.php

Joe-Strack, J. and Janowicz, J.R., 2009c. Yukon Snow Survey Bulletin and Water Supply Forecast: May 1 2009. Water Resources Branch, Department of Environment, Government of Yukon, 26 p. http://www.env.gov.yk.ca/air-water-waste/snow_survey.php

Lewis, P.R., Reynolds K. and Gagg, C. 2003. Forensic Materials Engineering. CRC Press, Taylor & Francis Group, 464 p.

Lyons, W.A., 2004. The role of litigation in the discovery of a probable undocumented F1 tornado in Munster, IN (27 June, 1995). 22nd Conference on Severe Local Storms, Fort Collins, MN, October 3-8, 2004.

McGregor, R.V., Hassan, M. and Hayley, D., 2008. Climate Change Impacts and Adaptation: Case Studies of Roads in Northern Canada. Transportation Association of Canada, Toronto, ON, p. 1-15.

Munich Re Group, 1997. Flooding and Insurance. Munich Reinsurance Group, Munich, Germany, 77 p.

NCE (Northern Climate ExChange), 2011a. Pelly Crossing Landscape Hazards: Geological Mapping for Climate Change Adaptation Planning. Yukon Research Centre, Yukon College, 48 p. and 2 maps.

NCE (Northern Climate ExChange), 2011b. Mayo Landscape Hazards: Geological Mapping for Climate Change Adaptation Planning. Yukon Research Centre, Yukon College, 64 p. and 2 maps.

Noon, R.K., 2000. Forensic Engineering Investigation. CRC Press LLC, Florida, USA, 451 p.

Osterkamp, T.E., 2003. A thermal history of permafrost in Alaska. Proceedings of Eighth International Conference on Permafrost, Zurich, p. 863-868.

Pearce, T., Ford, J.D., Prno, J. and Duerden, F., 2009. Climate change and Canadian mining: Opportunities for Adaptation. Prepared by ArcticNorth Consulting for The David Suzuki Foundation, 160 p. http://www.davidsuzuki.org/publications/downloads/2009/Climate_Change_And_Canadian_Mining.pdf

Rawlings, M., Bianchi, R. and Douglas, R.A., 2009. Winter roads and ice bridges: Anomalies in their records of seasonal usage and what we can learn from them. Transportation Association of Canada, Vancouver, BC, p. 1-14.

Romanovsky, V.E., Smith, S.L. and Christiansen, H.H., 2010. Permafrost Thermal State in the Polar Northern Hemisphere During the International Polar Year 2007-2009: A synthesis. Permafrost and Periglacial Processes, vol. 21, issue 2, p. 106-116.

Swiss Re, 1997. Tropical Cyclones. 201_9678, Swiss Reinsurance Company, Zurich, Switzerland.

Stephenson, S.R., Smith, L.C. and Agnew, J.A., 2011. Divergent long-term trajectories of human access to the arctic. Nature Climate Change, vol. 1, p. 156-160.

Transportation Association of Canada (TAC), 2010. Guidelines for development and maintenance of transportation infrastructure in permafrost regions (PTM-PERMAFROST). Transportation Association of Canada.

UNDP (United Nations Development Programme), 2013. A comparative review of country-level and regional disaster loss and damage databases. Bureau for Crisis Prevention and Recovery, New York, USA, 51 p.

UNEP (United Nations Environment Programme), 2012. Policy implications of warming permafrost. United Nations Environment Programme, 38 p.

APPENDIX A - INTERVIEW GUIDE FOR MINING SECTOR

We are conducting a study on the climate and weather information needs of the mining and transportation sectors in the North, with a focus on snow and permafrost. What we are trying to learn is what you as a practitioner feel are the most significant impacts that snow and permafrost have on your field of expertise, and what tailored information – what we are calling 'knowledge products' – can be developed to serve your needs.

Notes for Interviewers:

- The project embodies two main goals: hazard identification and information needs identification
- A number of questions may have already been answered in passing prior to their appearance in this form, with several specific examples indicated below; these can be mentioned in passing as the form is completed, but remain cognizant of repetition and interview duration.
- Double bordered 'boxed-in' questions can be skipped for the sake of time if interview is running long; the main purpose of the project is to identify and prioritize hazards and information needs, and to help develop knowledge products, and so questions addressing these should be given priority. Please indicate in your notes if the question was skipped.

<table>
<tr><td colspan="2">Name and Job Title:</td><td>Date of Interview:</td></tr>
<tr><td>Field of Expertise:</td><td colspan="2">Geographical Location (where you operate):</td></tr>
<tr><td colspan="3">Personal Background: (how long in this position; in this industry or related field; working in the north, etc.)</td></tr>
<tr><td colspan="3">Organization Background: (how long have they been operating; what stage are they in; what type of mining, etc.)</td></tr>
</table>

1) What weather and climate-related hazards or risks, both short and long term, do you consider in your work? [Note that we are focusing on permafrost and snow-related issues, but these could also include components *related* to these issues (e.g., freeze-thaw cycles).]

   a) Can you rank these hazards/risks (i.e., top 3) in terms of importance?
   *[**Note:** Interviewee may not be comfortable with actual ranking; make a note of this and continue.]*

   b) Are these hazards/risks happening with more or less frequency?

   c) How do these hazards or risks impact:
   *[**Note:** Interviewer may skip some of the following phase if it is outside of interviewee's experience.]*

      - Planning?
      - Design?
      - Operations?
      - Closure?
      - Decommissioning?
      - Remediation?

   d) How did you respond to these hazards/risks?
   *[**Note:** If responses to hazards have already been identified and noted above, then skip and move on.]*

   e) The following table provides a list of other potential hazards/risks that may impact your work:
   *[**Note:** Skip any impacts that have already been covered.]*

Table 1. Specific Climate and Weather Impacts.

Climate/Weather Impact	How does this impact your planning/operation/ remediation?	How do you respond or plan for this?
Soil bearing capacity failure due to permafrost thaw (roads, building foundations, mining tailings systems, etc.)		
Site access/mobility/operations restrictions from snowfall accumulations		
Loss of ice roads due to shortened operating seasons; increases in transportation/ supply services costs due to switch to air travel		
Damage due to heavy snow/ ice loading to buildings and infrastructure (either heavy snow loads, rain-on-snow, ice storms)		

Table 1. Specific Climate and Weather Impacts, *continued.*

Climate/Weather Impact	How does this impact your planning/operation/ remediation?	How do you respond or plan for this?
Seasonal changes and/or increases in severity of snow melt and runoff, spring flooding, and related issues (e.g., tailings management systems, road salt, etc.)		
Reduced visibilities due to blowing/falling snow		
Avalanche hazards to transportation or other operations		
Damage to infrastructure from freeze-thaw cycling		
Others not covered here? Please specify: ______ ______ ______		

2) Have you noticed any changes in climate over the course of your career, both short term and long term? (Please describe time frame involved.)

3) What weather and climate information do you typically use, and where do you access this information?

   a) What types of weather and climate information could you use that you don't already have access to? (For example, the timing and water equivalent of the maximum snowpack, information on a 30-year, worst-case snowfall.)

   b) Have you ever suffered an inability to make decisions due to poor quality and/or unavailable data?

   c) What kinds of products would best communicate the information that you need?
   *[See **Table 2** below for a list of additional suggestions.]*

Table 2. Possible Weather/Climate Information Products.

Product	Would this be useful?
Online interactive maps or learning modules	
Easily accessible data sets for decision making (please specify needed content)	
Maps, graphs, nomograms* or other graphical guidance or representations in guidelines/ standards/codes, etc.	
More up-to-date climate information for infrastructure codes and standards	

Table 2. Possible Weather/Climate Information Products, *continued.*

Product	Would this be useful?
Thresholds for significant impacts (i.e., forensic studies), as well as notice (warnings or advisories) when these thresholds are reached near real-time	
Climate or weather-related training (e.g., forecasting/weather information interpretation, monitoring, etc.)	
Guidelines for more consistent climate-change assessments (e.g., design, closure and monitoring of mines based on International Panel on Climate Change (IPCC) suggested guidelines, assessing impacts of climate change on winter roads, etc.)	
Easy-to-use indices linking winter severity with maintenance costs (e.g., "Winter Severity Index" for roads in southern Canada; Suggett et al., 2006)	
Infrastructure Health Monitoring (IHM); continuous recording of structures and infrastructure with embedded sensors and meteorological observations (e.g., Sidawi and Shehata 2008)	

******Nomograms are often used in meteorology and consist of 2-D graphs that show important thresholds or ranges for important factors. For example, nomograms of use to mining and transportation could include wind speeds versus visibility in blowing snow, or perhaps snow depth versus impacts on operations.*

d) If you think guidelines and similar documents would be useful, what main subjects/outline headings can you picture being of importance, i.e., what would the table of contents look like?

4) In your work, do you use any 'threshold' values for snow or permafrost-related hazards/risks? If yes, what are they? (For example, snowfall depths or minimum visibility values that are important for operations, maintenance or safety; active layer depths which are problems for infrastructure/facilities design and maintenance.)

5) What guides, standards and/or codes (if any) are most important to your profession?

   a) Do they address extreme weather and climate-change impacts? If not, can you explain?

   b) Are there snow/permafrost-related measures in guides that are widely ignored? If yes, please explain?

   c) Would it help in promoting understanding or compliance if an explanation is provided of how code values or criteria were developed?

6) Are you aware of any climate and mining-related research being conducted in Canada or in similar regions abroad (i.e., cold-region engineering, adaptation, etc.)?

   a) If so, can you please indicate those initiatives of greatest potential relevance to designing and managing for the changing permafrost and snow conditions?

7) Do you know of any colleagues who would be good candidates for interviews/discussion of the topics we've addressed (i.e., people with long careers and/or a strong interest in these types of issues)?

8) Are you aware of any existing climate models and projections in your area?

    a) Would you use them? Why or why not?

9) Does the term 'climate adaptation' mean anything to you? How do you interpret 'adaptation'?

10) What climate adaptation programs or measures related to your work are you aware of?

    a) Are you aware of any that are/were either ineffective or could be improved? Please elaborate.

11) What is your sense of the 'climate and climate change awareness' within your organization? (For example, is there climate-change skepticism or a sense that all that can be done for adaptation is already being done?)

REFERENCES

Suggett, J., Hadayeghi, A., Mills, B., Andrey, J. and Leach, G., 2006. Development of winter severity indicator models for Canadian winter road maintenance. Transportation Association of Canada, Charlottetown, PEI, p. 1-20.

Sidawi, S. and Shehata, E., 2008. Using Infrastructure Health Monitoring (IHM) to assess the impact of climate change on civil infrastructure. Maintenance & Construction Technical Paper Session: Impact of climate change on infrastructure construction, maintenance and operations; Annual Conference of the Transportation Association of Canada, Toronto, ON, September 21-23, 2008, 12 p.

APPENDIX B - INTERVIEW GUIDE FOR TRANSPORTATION SECTOR

We are conducting a study on the climate and weather information needs of the mining and transportation sectors in the North, with a focus on snow and permafrost. What we are trying to learn is what you as a practitioner feel are the most significant impacts that snow and permafrost have on your field of expertise, and what tailored information – what we are calling 'knowledge products' – can be developed to serve your needs.

Notes for Interviewers:

- The project embodies two main goals: hazard identification and information needs identification
- A number of questions may have already been answered in passing prior to their appearance in this form, with several specific examples indicated below; these can be mentioned in passing as the form is completed, but remain cognizant of repetition and interview duration.
- Double bordered 'boxed-in' questions can be skipped for the sake of time if interview is running long; the main purpose of the project is to identify and prioritize hazards and information needs, and to help develop knowledge products, and so questions addressing these should be given priority. Please indicate in your notes if the question was skipped.

Name and Job Title:	Date of Interview:
Field of Expertise:	Geographical Location (where you operate):
Personal Background: (how long in this position; in this industry or related field; working in the north, etc.)	
Organization Background: (how long have they been operating; how are they involved in the transportation industry; etc.)	

1) What weather and climate-related hazards or risks, both short and long term, do you consider in your work? [Note that we are focusing on permafrost and snow-related issues, but these could also include components *related* to these issues (e.g., freeze-thaw cycles).]

    a) Can you rank these hazards/risks (i.e., top 3) in terms of importance? *[**Note:** Interviewee may not be comfortable with actual ranking; make a note of this and continue.]*

    b) Are these hazards/risks happening with more or less frequency?

    c) How do these hazards or risks impact: *[**Note:** Interviewer may skip some of the following phase if it is outside of interviewee's experience.]*

        - Design?
        - Planning?
        - Construction?
        - Operations?
        - Mintenance?

    d) How did you respond to these hazards/risks? *[**Note:** If responses to hazards have already been identified and noted above, then skip and move on.]*

    e) The following table provides a list of other potential hazards/risks that may impact your work: *[**Note:** Skip any impacts that have already been covered.]*

Table 1. Specific Climate and Weather Impacts.

Climate/Weather Impact	How does this impact your planning/operation/ maintenance?	How do you respond or plan for this?
Soil bearing capacity failure due to permafrost thaw (roads, building foundations, etc.)		
Site access/mobility/operations restrictions from snowfall accumulations		
Loss of ice roads due to shortened operating seasons; increases in transportation/ supply services costs due to switch to air travel		
Damage due to heavy snow/ ice loading to buildings and infrastructure (either heavy snow loads, rain-on-snow, ice storms)		

Table 1. Specific Climate and Weather Impacts, *continued.*

Climate/Weather Impact	How does this impact your planning/operation/ maintenance?	How do you respond or plan for this?
Seasonal changes and/or increases in severity of snow melt and runoff, spring flooding, and related issues (e.g., road salt)		
Reduced visibilities due to blowing/falling snow		
Avalanche hazards to transportation or other operations		
Damage to infrastructure from freeze-thaw cycling		
Others not covered here? Please specify: ______________ ______________ ______________		

2) Have you noticed any changes in climate over the course of your career, both short term and long term? (Please describe time frame involved.)

3) What weather and climate information do you typically use, and where do you access this information?

   a) What types of weather and climate information could you use that you don't already have access to? (For example, the timing and water equivalent of the maximum snowpack, information on a 30-year, worst-case snowfall.)

   b) Have you ever suffered an inability to make decisions due to poor quality and/or unavailable data?

   c) What kinds of products would best communicate the information that you need?
   *[See **Table 2** below for a list of additional suggestions.]*

Table 2. Possible Weather/Climate Information Products.

Product	Would this be useful?
Online interactive maps or learning modules	
Easily accessible data sets for decision making (please specify needed content)	
Maps, graphs, nomograms* or other graphical guidance or representations in guidelines/ standards/codes, etc.	
More up-to-date climate information for infrastructure codes and standards	

Table 2. Possible Weather/Climate Information Products, *continued.*

Product	Would this be useful?
Thresholds for significant impacts (i.e., forensic studies), as well as notice (warnings or advisories) when these thresholds are reached near real-time	
Climate or weather-related training (e.g., forecasting/weather information interpretation, monitoring, etc.)	
Guidelines for more consistent climate-change assessments (e.g., assessing impacts of climate change on winter roads, etc.)	
Easy-to-use indices linking winter severity with maintenance costs (e.g., "Winter Severity Index" for roads in southern Canada; Suggett et al., 2006)	
Infrastructure Health Monitoring (IHM); continuous recording of structures and infrastructure with embedded sensors and meteorological observations (e.g., Sidawi and Shehata 2008)	

**Nomograms are often used in meteorology and consist of 2-D graphs that show important thresholds or ranges for important factors. For example, nomograms of use to mining and transportation could include wind speeds versus visibility in blowing snow, or perhaps snow depth versus impacts on operations.*

d) If you think guidelines and similar documents would be useful, what main subjects/outline headings can you picture being of importance, i.e., what would the table of contents look like?

4) In your work, do you use any 'threshold' values for snow or permafrost-related hazards/risks? If yes, what are they? (For example, snowfall depths or minimum visibility values that are important for operations, maintenance or safety; active layer depths which are problems for infrastructure/facilities design and maintenance.)

5) What guides, standards and/or codes (if any) are most important to your profession?

   a) Do they address extreme weather and climate-change impacts? If not, can you explain?

   b) Are there snow/permafrost-related measures in guides that are widely ignored? If yes, please explain?

   c) Would it help in promoting understanding or compliance if an explanation is provided of how code values or criteria were developed?

6) Are you aware of any climate and transportation-related research being conducted in Canada or in similar regions abroad (i.e., cold-region engineering, adaptation, etc.)?

   a) If so, can you please indicate those initiatives of greatest potential relevance to designing and managing for the changing permafrost and snow conditions?

7) Do you know of any colleagues who would be good candidates for interviews/discussion of the topics we've addressed (i.e., people with long careers and/or a strong interest in these types of issues)?

8) Do you know of, and do you use, any computer-based training modules and decision-making platforms for road maintenance management? (Some already exist and could be tailored to northern needs.)

9) Are you aware of any existing climate models and projections in your area?

    a) Would you use them? Why or why not?

10) Does the term 'climate adaptation' mean anything to you? How do you interpret 'adaptation'?

11) What climate adaptation programs or measures related to your work are you aware of?

    a) Are you aware of any that are/were either ineffective or could be improved? Please elaborate.

12) What is your sense of the 'climate and climate change awareness' within your organization? (For example, is there climate-change skepticism or a sense that all that can be done for adaptation is already being done?)

REFERENCES

Suggett, J., Hadayeghi, A., Mills, B., Andrey, J. and Leach, G., 2006. Development of winter severity indicator models for Canadian winter road maintenance. Transportation Association of Canada, Charlottetown, PEI, p. 1-20.

Sidawi, S. and Shehata, E., 2008. Using Infrastructure Health Monitoring (IHM) to assess the impact of climate change on civil infrastructure. Maintenance & Construction Technical Paper Session: Impact of climate change on infrastructure construction, maintenance and operations; Annual Conference of the Transportation Association of Canada, Toronto, ON, September 21-23, 2008, 12 p.

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Abbreviations:

EC – Environment Canada

ENSO – El Niño Southern Oscillation

GCM – global climate model

IPCC – United Nations International Panel on Climate Change

MAC – Mining Association of Canada

NAO – North Atlantic Oscillation

NWT – Northwest Territories

PDO – Pacific Decadal Oscillation

RCM – regional climate model

SCE – snow cover extent

SWE – snow water equivalent

TAC – Transportation Association of Canada

1. INTRODUCTION

The project "Enhancing Knowledge Transfer to Decision Makers with Respect to Climate Change Impacts on the Cryosphere", hereafter known as the Cryosphere project, focuses on developing methods to identify the climate and weather-related needs of decision makers whose professions are directly impacted by climate and weather. Researchers from the Northern Climate ExChange and Risk Sciences International are leading the work to consolidate and identify gaps in existing knowledge, understanding and awareness of the impacts of northern climate change on permafrost and snow in the northern mining and transportation sectors. Additional organizations making up the Project Team include University of Ottawa, OCCIAR, Mirarco and Government of the Northwest Territories, Department of Transportation.

The Cryosphere project focuses on the needs of practitioners in the mining and transportation sectors in northern Canada, specifically in Yukon and the Northwest Territories (NWT), and on the impacts of permafrost and snow – two climate elements which are expected to be heavily influenced by climate change. A literature review was completed to inform other elements of the project, including development of an interview guide, identification of project advisors and interview respondents, and development of knowledge products. This report summarizes the literature review that was completed by Project Team members from Risk Sciences International, University of Ottawa and the Northern Climate ExChange.

The literature review focuses on the impacts of snow, permafrost and their interactions on surface transportation and mining in the Canadian territories of Yukon and NWT. This report introduces definitions of the main components of the research project as well as their parameters. This report includes a review of climate interactions with both snow and permafrost and incorporates expected future changes. In regards to the mining and transportation sectors, this report will discuss the relative importance of climate change impacts, the benefits and limitations of related adaptation measures, and gaps and limitations in the available knowledge and research. While discussion of these results will focus on the northern Canadian region, and specifically Yukon and NWT, several examples of relevant tools and research developed and conducted in other regions will also be examined.

In this report, references to ‘the North’ refer to Yukon and the Northwest Territories, and more broadly to parts of Canada north of 60° N. While the current study focuses on these two territories, research and discussions referring to Nunavut and Alaska have also been used for illustrative purposes. We acknowledge the variability and complexity of the climate and geography of the region under study, but a lack of observational data and associated research requires that some generalization and acceptance of uncertainty is necessary.

This report will include a review of climate-permafrost interactions, permafrost distribution modelling, and climate change impacts on mining and transport infrastructure in the North.

2. DEFINITIONS

2.1. Permafrost

Permafrost is defined as ground material that remains at or below 0°C for two or more consecutive years. Permafrost regions occupy approximately 24% of the terrestrial surface of the Northern Hemisphere at high latitudes, known as latitudinal permafrost, and at high altitudes known as mountain or alpine permafrost. This ground thermal regime is generally present when mean annual air temperature is at or below -2°C, but can also be present as relict permafrost in environments that may no longer be suitable for the formation of permafrost, for example sub-sea environments. Permafrost should not be considered ‘permanent’ because it is always in dynamic equilibrium with changing climatic conditions. As such, permafrost is perennially, not permanently, frozen ground.

Permafrost is classified based on spatial distribution into four zones termed continuous (>90%), extensive discontinuous (50-90%), sporadic discontinuous (10-50%), and isolated patches (<10%). Two other zones exist: alpine permafrost (which is associated with elevation) and subsea permafrost. Permafrost can also be classified based on its characteristics, for example the thermal regime (warm or cold), ice content (ice-rich or ice-poor), ice type (visible or non-visible), and depth (deep or shallow).

The active layer of permafrost is typically 20-200 cm deep (from the ground surface down) and freezes and thaws due to positive and negative seasonal air temperature fluctuations (Figure 1). Beneath the active layer is the seasonally inactive base layer, which remains frozen throughout the year. The depth of the base layer of permafrost is controlled by the climatic regime, the geothermal heat flux, and the thermal conductivity of the frozen ground material.

Ground ice refers to all types of ice contained in freezing and frozen ground. Ground ice can occur in soil and bedrock. Ground ice can exist in the pores of the ground, or it can form ice lenses and veins. The term ‘excess ice’ is applied when the total water content of the frozen ground exceeds the total water content of its normally consolidated state when unfrozen. When ice-rich permafrost thaws, the ground will settle under its own weight until it attains a consolidated state. Excess ice can be distributed or segregated into lenses within the frozen soil. In extreme cases, ice can form massive inclusions that exceed the volume of soil particles. Massive ice can be tens of metres thick and can be hundreds of metres wide. Such landforms are common in Arctic coastal environments in North America and Russia. This ice is thought to originate from covered glacial ice. It is the nature and genesis of ground ice that determines how the permafrost will behave under load and its sensitivity to thawing. An early assessment of ground ice conditions is critical to developing a strategy for all types of construction over permafrost soils.

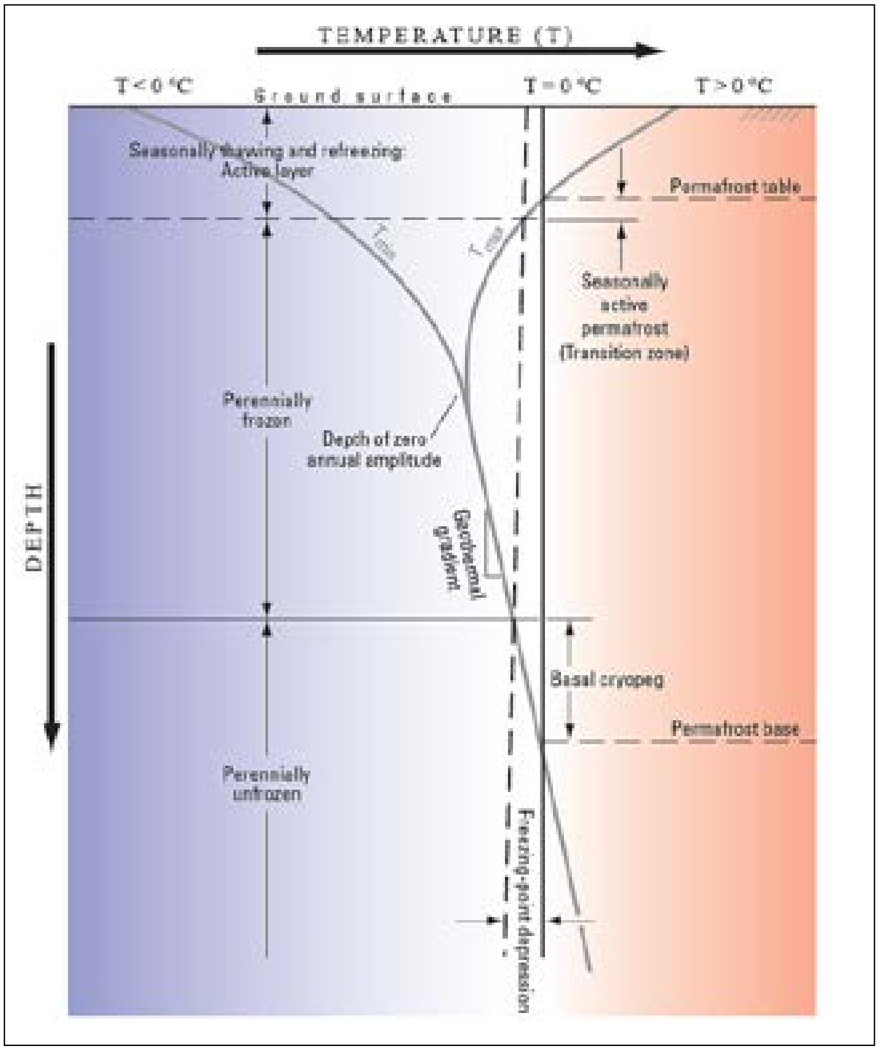

Figure 1. *Terminology of the ground temperature profile relative to 0°C in a permafrost environment (Heginbottom et al., 2012).*

Thermokarst defines geomorphology developed by the thawing of ground ice. When ice-rich permafrost thaws, there are associated subsidence and cave-in formations (e.g., thermokarst ponds and thaw lakes). Rapid thaw of ice-rich permafrost generally does not allow for proper drainage of the resulting meltwater and can cause ground failure (complete loss of strength). Slow thaw of ice-rich permafrost will usually drain properly and cause the ground to sink (also known as ground subsidence) without failure.

Slope failures such as detachments, thaw slumps, and solifluction occur in angled ice-rich permafrost. Causes may include a warm summer with a deep active layer, wildfire, or heavy rain. Detachment failures occur mostly on south-facing slopes with angles as low as 6°. Thaw slumps occur progressively on slopes as a bowl shape with a steep headwall that exposes the ice-rich permafrost. The headwall warms in summer and detaches with the net effect of retreating the headwall and enlarging the thaw slump.

Permafrost-related definitions were collected and compiled from French (2007), Burn (2007), Brown et al. (1997), Heginbottom et al. (2012), van Everdingen (2005), and TAC (2010).

2.2. Snow

Meteorological conditions at the time of snowfall, particularly temperature and moisture distribution, determine the growth and accumulation rates of snow, as well as the shape and water content of snow crystals. Crystal shape and water content further impact the packing density of freshly fallen snow, which can vary significantly depending on conditions. For example, the heaviest snow tends to occur when formation occurs within a deep layer of moist air that is near 0°C but below freezing. Following the snowfall, the snowpack then evolves through other processes such as melting, sublimation, and displacement by wind, the latter being a particularly important process in the arctic and sub-arctic regions (Phillips, 1990; Mekis and Brown, 2010).

Snow cover extent (SCE) is the area covered by snow in a given region. It is generally expressed as a percentage. SCE is particularly important due to its impacts on surface albedo (reflectivity), and it is also the most easily detected and measured of snow quantities. Snow depth (D) is either measured by the amount of snow that has fallen during a certain time period (e.g., one hour or one day accumulations) or by the 'snow-on-ground' (SOG), which is simply the total depth of the current snowpack present on the ground. Both are usually reported in units of centimetres. Snow density (ρ) is the mass per unit volume of a given snow sample. Snow water equivalent (SWE) is the total depth of equivalent water of the snowpack, usually expressed in millimetres. These last two measures are particularly important for many of the snow-related impacts discussed below.

3. Climate Change and the Cryosphere

Recent and projected changes in climate (i.e., mostly increased air temperature and precipitation) are expected to rapidly impact certain aspects of the cryosphere, with the greatest changes occurring at high latitudes (ACIA, 2005; Lemke et al., 2007). These impacts on the cryosphere will not only affect ecosystems and local climate, but also man-made infrastructure. Modelling climate change is a challenging task because the climate signal of recent change, commonly attributed to anthropogenic emission of greenhouse gases, is overlain on climate signals from unrelated long-term climate patterns (i.e., those responsible for the most recent glaciation that ended about 15,000 years ago, such as Milankovitch cycles, solar cycles, etc.; Benn and Evans, 2010). Observation and monitoring networks across the Arctic are recording rapid changes to the landscape, climate, ecology, and even the composition of the atmosphere. Although many of these changes themselves are not unprecedented, it seems that the rate at which these changes are occurring is unprecedented (Zdanowicz et al., 2012).

3.1. Pan Arctic Perspective

The IPCC has summarized the general findings for climate change expected in the Polar Regions in Chapter 15 of their latest summary (Anisimov et al., 2007)[1]. Globally, the most rapid observed warming of recent decades has occurred in subregions of the Arctic, including northwestern North America. Most of that warming occurs during winter and spring, the effects of which we may already be witnessing in snow cover extent (SCE) studies (Derksen and Brown, 2012). Observed trends currently indicate a generally small (1%) increase in precipitation across the Arctic, but local results are highly variable, and difficulties associated with deficiencies in precipitation network density and precipitation measurement in windy environments make trend and attribution studies in Polar Regions extremely difficult. Global increases of 10-20% in

1. Results of the last several years are soon to be updated in the next IPCC summary, AR5, due for release in 2014.

precipitation are expected by the end of the century, resulting in increases of 10-30% for Arctic river discharge into the Arctic Ocean (Anisimov et al., 2007).

3.2. Climate Change and Permafrost

Permafrost has three roles in the climate system: as an archive of climatic change at depth, as a vehicle for transferring atmospheric temperature changes to the hydrological and biological components of the earth (including humans), and as a feedback to climate change through the release of trace gases when thawing, such as CO_2 and CH_4 (Nelson et al., 2002).

3.2.1. Changes in Permafrost

3.2.1.1. Recent changes in permafrost

Increases in permafrost temperatures have been observed in North America, Europe and Eurasia. In Alaska, a network of deep boreholes has shown that since the early 1980s, permafrost at a depth of 20 m has warmed between 0.5°C and 2°C (UNEP, 2012; Osterkamp, 2003).

In ice-rich permafrost, heat is absorbed to melt ice as the frozen ground approaches zero degrees Celsius. Warming trends are often absent in warm (>-1°C) ice-rich permafrost, because temperatures remain just below zero until all of the ice melts (UNEP, 2012).

3.2.1.2. Carbon release from permafrost

Schuur et al. (2008) state that thawing permafrost and the resulting decomposition of previously frozen organic carbon (C) is one of the most significant potential feedbacks from terrestrial environment to the atmosphere in a changing climate. As permafrost thaws, carbon is transferred to the terrestrial, marine, and atmospheric carbon reservoirs. The relative proportions of carbon transferred to these different reservoirs presents a monumental challenge to our understanding of the processes at hand and our ability to model them. The authors estimate a release of 100 petagrams (1 petagram = 1×10^{12} kg) of carbon from permafrost by 2100 due to thawing.

Tarnocai et al. (2009) have presented a database, the Northern Circumpolar Soil Carbon Database that estimates the size and the spatial distribution of organic carbon pools in the North. They estimate that the total amount of carbon stored in soils worldwide ranges from 1395 to 1576 petagrams in the first metre, 491 petagrams in the second metre, and 351 petagrams in the third metre of permafrost.

3.2.2. Permafrost, Mining and Transportation

The study of permafrost has become significant in regards to cold region engineering due to recent observations and predictions of climate change, specifically warming, in the North. Permafrost is often conceptualized as being locally uniform through space and time, though in reality permafrost is highly heterogeneous. This is a very challenging environment for construction. Changes in the distribution and characteristics of permafrost are expected to have broad impacts on ecosystems, infrastructure (e.g., buildings, roads, etc.), climate, and the economy. Many permafrost regions are remote and sparsely populated, and contain natural resources (e.g., timber, minerals, oil and natural gas).

Permafrost temperatures have increased during the last 20–30 years in almost all areas of the Northern Hemisphere (Romanovsky et al., 2010). An increase in the depth of the active layer (that part of permafrost that thaws each summer) above the permafrost is less certain. Predicted increases in air temperatures for the 21st century are projected to initiate widespread permafrost thawing in the subarctic and in mountain regions in both hemispheres. Widespread thawing of permafrost will speed up the decomposition of organic material previously held frozen in permafrost, emitting large amounts of greenhouse gases into the atmosphere. Thawing of ice-rich permafrost may also have serious consequences for ecosystems and infrastructure, and in mountain regions, it may reduce the stability of slopes and increase the danger of rock falls and landslides.

3.2.3. Permafrost Distribution

Permafrost in the Northern Hemisphere covers an area of ~22.8 million km^2 (Figure 2), has a volume of ~4.5 million km^3, and represents a potential for sea level rise of ~7 cm (IPCC, 2007). Seasonal freezing of the ground (not necessarily permafrost), on the other hand, affects an area of ~48 million km^2 (Zhang et al., 2003). In Canada, permafrost encompasses about 50% of the total land mass (Smith and Riseborough, 2002). The northern limit of discontinuous permafrost occurs between mean annual air temperatures of -6°C and -8°C, and the southern limit of

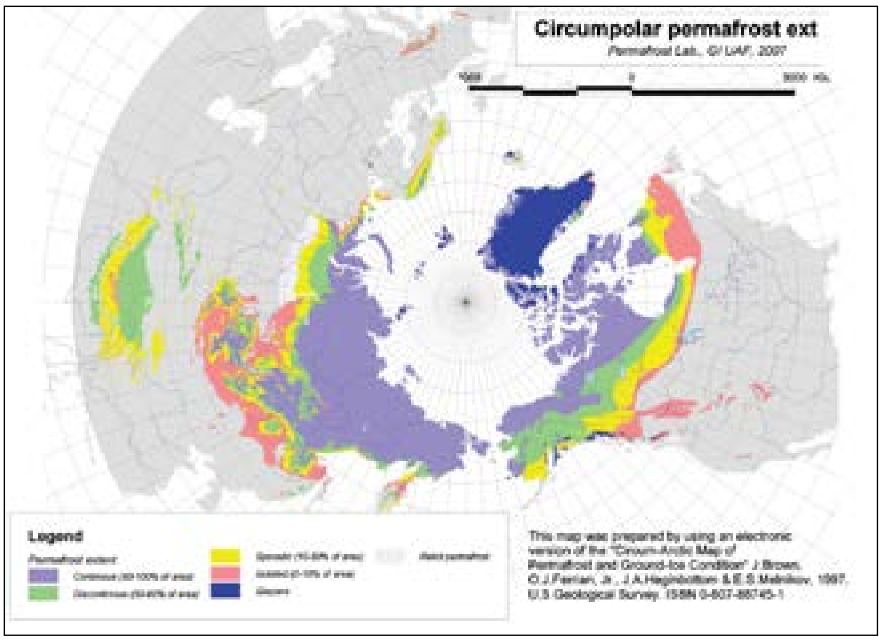

Figure 2. *Generalized permafrost map of the Northern Hemisphere, including the limit of subsea permafrost, based on the International Permafrost Association Circum-Arctic Map (Heginbottom et al., 2012).*

discontinuous permafrost occurs below the -1°C isotherm. Other factors, including snow cover, thermal conductivity of the ground, and vegetation, may also influence the distribution and characteristics of permafrost (Smith and Riseborough, 2002).

Figure 3 demonstrates generalized trends of climate and permafrost with regards to latitude. As latitude increases and mean annual air temperature (MAAT) decreases, the active layer decreases in depth and permafrost gradually transitions from sporadic to continuous. Altitudinal or mountain permafrost may persist in the absence of lower elevation permafrost (e.g., alpine or mountainous terrain). Figure 4 demonstrates the relationship between permafrost distribution, slope aspect (e.g., north-facing, south-facing, etc.) and elevation.

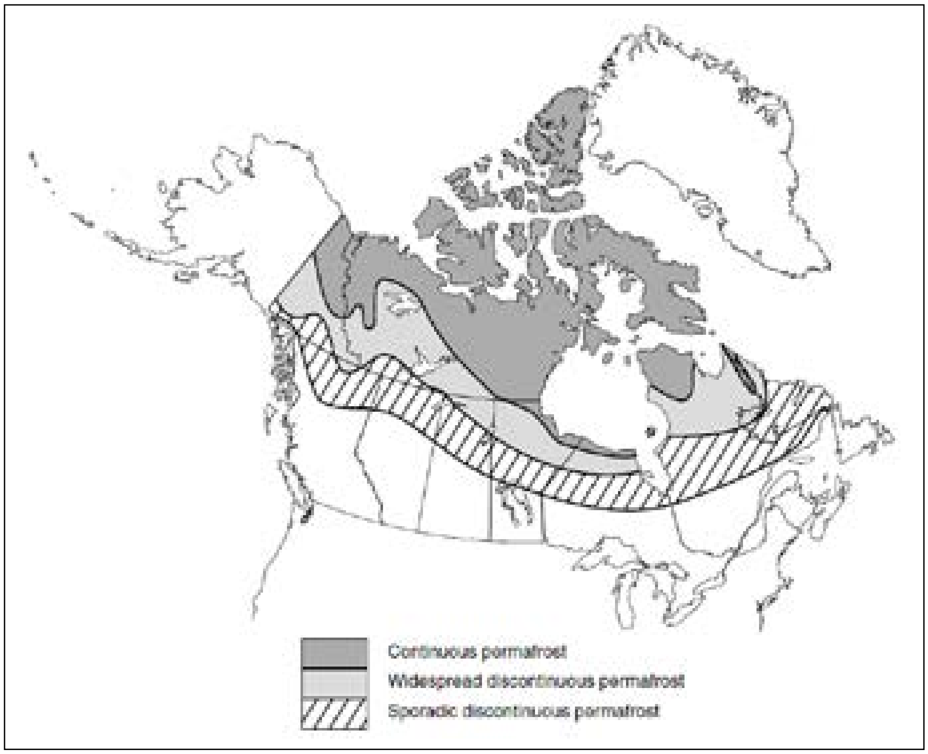

Figure 3. *Permafrost regions of Canada (Smith and Riseborough, 2002).*

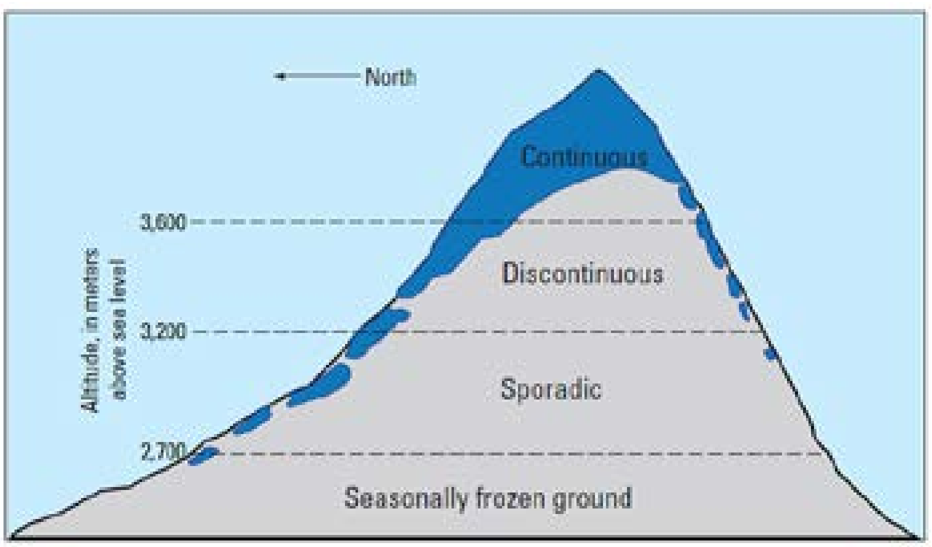

Figure 4. *Idealized diagram of altitudunal distribution of sporadic, discontinuous and continuous permafrost (Heginbottom et al., 2012).*

3.2.4. Monitoring Permafrost

Determining the presence or absence of permafrost is not always a straightforward task, especially in the discontinuous or mountain permafrost zones. Techniques to determine the presence of permafrost include drilling deep or shallow boreholes and monitoring ground temperatures, geophysical investigations, climate monitoring, mapping periglacial geomorphology, and remote sensing techniques. Experts in the field also usually rely on their 'hunch' or 'gut feeling' as a preliminary assessment of the presence of permafrost in a given location. This phenomenon often involves expert interpretation of surface features such as vegetation, topography, soil, etc.

Drilling boreholes in order to analyze a sediment or bedrock core or to install ground temperature sensors is an excellent method to determine the presence of permafrost and describe its characteristics. Unfortunately, drilling is often costly and logistically difficult, especially in remote areas. Many drilling techniques exist, from large drilling rigs to smaller hand drills. An important consideration when drilling in discontinuous permafrost is that the process of drilling may cause the thaw of the permafrost; this is common in water-jet drilling. Furthermore, it is important to consider that if a borehole is instrumented with ground temperature sensors, it will require in situ downloading of the data (unless there is cellular or satellite communication) and regular maintenance (e.g., replacing batteries, unless equipped with a solar panel). The Circumpolar Active Layer Monitoring program (CALM) and the Thermal State of Permafrost network (TSP) are two permafrost monitoring networks that respectively monitor 260 and 860 boreholes of varying depths located around the world.

Geophysical investigations involve techniques such as Electrical Resistivity Tomography (ERT) and Ground Penetrating Radar (GPR). ERT is a 2D or 3D imaging technique of the subsurface that is highly sensitive to the transition between frozen and unfrozen materials. This technique has been successfully applied to the mapping and characterization of shallow permafrost (<30 m depth penetration) in mountain terrain (Harris et al., 2009). Repeat surveys, borehole logs, and borehole temperature records serve to calibrate and enhance certainty using this low-cost and non-intrusive method. GPR is being used to map permafrost distribution and structure, and it is best suited to investigate the active layer and ice-rich permafrost (Jørgensen and Andreasen, 2007; Harris et al., 2009). Other methods also exist, including refraction seismics, crosshole methods, electromagnetic induction mapping, among others. Ideally, studies should combine two or more methods along with borehole drilling.

Remote sensing is not directly used to identify the presence of permafrost. The presence of permafrost and its characteristics cannot be determined by conventional aerial or satellite remote sensing (Heginbottom et al., 2012). However, surface indicators of permafrost can be identified with high-resolution images.

3.2.5. Spatial Modelling

The spatial modelling of permafrost is often achieved through various combinations of direct (e.g., drilling, digging) or indirect (e.g., geophysical surveys, BTS (basal temperature of snow) measurements) observations of permafrost, conceptual thermal relationships (e.g., Stefan model, Kudryavtsev model) and spatial data. Two approaches to modelling are discussed below: empirical-statistical models and process-based models. These models often use a combination of climatic conditions and the properties of earth surface and subsurface properties to determine the ground thermal regime.

Empirical-statistical permafrost models are steady-state models that use regression functions to associate the presence of permafrost with topo-climatic factors (e.g., altitude, slope angle and aspect, mean air temperature, solar radiation; Bonnaventure, 2006; Harris et al., 2009). As such, modelling the complex ground surface exchanges (e.g., latent heat exchanges, vegetation) is not necessary. These models are relatively simple because they require limited inputs. Usually based on a digital elevation model (DEM), these models will generate permafrost probability or mean ground temperature values in the form of a gridded surface output (Bonnaventure, 2006; Riseborough et al., 2008). Although they are simpler to compute, empirical-statistical models require recalibration for different environments (Riseborough et al., 2008).

Process-oriented permafrost models are more complex and incorporate modelled energy fluxes between the atmosphere and permafrost (e.g., solar radiation, turbulent heat fluxes, surface albedo, and heat conduction). These models require large amounts of data, and allow modelling through space and time. As opposed to a binary response to the presence or absence of permafrost, process-oriented models enable surface temperatures to be computed and, hence, thermal conditions at depth and transient effects in complex topography to be estimated (Bonnaventure, 2006; Riseborough et al., 2008).

Nelson et al. (2002) developed a hazard zonation map of the Northern Hemisphere that includes a northward shift of the southern limit of permafrost as well as an increase in active layer thickness. They used general circulation model scenarios of global climate change, mathematical solutions for the thickness of the active layer, and digital representations of permafrost distribution and ice content in the model. Areas of greatest hazard potential relating to thaw subsidence included coastlines on the Arctic Ocean and parts of Alaska, Canada and Siberia. While continental-scale maps are not useful for local decision making, they point to geographic areas where hazard scientists, policy analysts, and engineers should focus attention.

3.2.6. Engineering

Projected warming air temperatures could lead to increases in permafrost temperatures, thickening of the active layer, and reduced permafrost coverage. These changes can lead to extensive settlement of the ground surface, with possible damage to infrastructure (e.g., roads, bridges, buildings, utilities, pipelines, and airstrips).

Rehabilitating or abandoning community infrastructure damaged by thawing permafrost will be very costly, and in some cases, already has been. It is likely that most of the infrastructure that exists in permafrost regions will be heavily impacted by the disappearance of permafrost (USARC, 2003). These impacts include the release of contaminants, currently thought to be safely contained (e.g., landfills, tailings ponds) or even the displacement of villages (e.g., a study by the US Corps of Engineers estimated the cost of moving the village of Kivalina, Alaska to be US$154,000,000; USACE, 2006).

3.2.7. Snow and Permafrost Interactions

Snow cover influences local permafrost conditions because it is a good insulator. Heavy snowfall will prevent frost penetration into the ground, whereas light or absent snowfall will do the opposite. Late snowmelt in the spring will push back thawing of the ground. The influence of snow cover on permafrost is generally accepted to be more important in the discontinuous permafrost zone and less important in continuous permafrost. Smith and Riseborough (2002) have shown that snow can prevent the formation of permafrost. Figure 5 demonstrates this relationship, where deeper snow is required to prevent permafrost in colder regions.

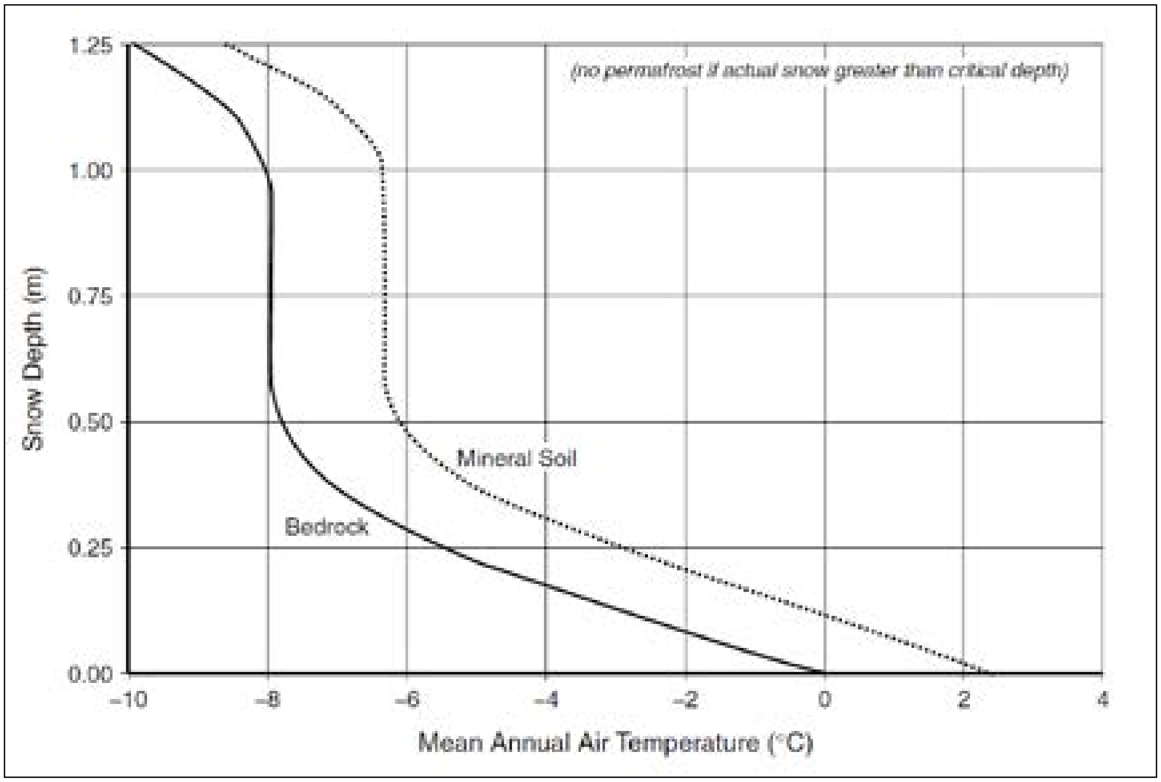

Figure 5. *Critical snow depth necessary to prevent permafrost occurrence at any mean annual air temperature (Smith and Riseborough, 2002).*

3.3. Climate Change and Snow

Though counterintuitive, climate change in high latitude regions may lead to greater total snow accumulations (seasonal water storage) while simultaneously generating shorter snow cover durations. The region will remain well below freezing during the winter months, even with significant warming of average temperatures, and hence the increased water 'carrying capacity' or vapour capacity of the warmer air[2] will likely dominate changes in snow characteristics. Broadly speaking, most studies assessing precipitation trends have found increases in global precipitation, with increases concentrated in the winter season and in the high latitudes (Stone et al., 2000). Regional studies have also emphasized the need to account for other long-term cycles and teleconnections such as the Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO), El Niño Southern Oscillation (ENSO), and so on, several of which are discussed below (Stone et al., 2000; Werner et al., 2009; Brabets and Walvoord, 2009; Janowicz, 2010). Given the sensitivity of the Arctic climate to other processes, the effects of anthropogenic climate change need to be separated from other natural cycles and processes which also play a role in short-term climate trends. Janowicz (2010), for example, has suggested that some of the very high temperatures experienced in Yukon in recent years have been due to (at least in part) a strong PDO influence.

2. The ability of air to retain water vapour increases exponentially with an increase in temperature, hence the heaviest snow with the greatest water content will occur when temperatures are just below freezing, cool enough to form snow, but warm enough to contain significantly more moisture than at colder temperatures.

3.3.1. Snow Cover

Räisänen (2008) was among the first to explicitly question whether climate change would lead to more or less snow in the northern cryosphere, employing a multi-model ensemble to determine whether or not GCMs came to a consensus on the issue. Attempting to interpret trends and project changes in snow characteristics from previous studies has yielded mixed results from various regions.

In an attempt to rectify this apparent conflict, Brown and Mote (2009) employed a snowpack model, combined with climate projections and satellite data, to determine the sensitivity of individual snow characteristics to specific climate drivers. They specifically sought any snow characteristics that would likely be the first to respond to climate change, and determined that snow cover duration was the most sensitive to temperature changes. Partial confirmation of these results was reported by Derksen and Brown (2012), who showed that the monthly averaged spring snow cover extent (SCE) for the Arctic has been significantly lower in recent years than was predicted by GCM ensembles, exhibiting greater than ±1 standard deviation from model consensus. The five lowest June SCE values have occurred in the most recent five seasons (2008-2012) and SCE declines have even outpaced Arctic sea ice extent losses which have been the subject of significant media coverage.

3.3.2. Snow Water Equivalent

Snow water equivalent (SWE) is among the most difficult of the snow variables to measure, which complicates interpretations of trends and future projections. Remote sensing through satellite imagery (passive microwave sensing), for example, is prone to significant biases in SWE estimates. One study notes that errors of up to ~40 mm may occur (Howell et al., 2012), while another study assessing snow cover in the former Soviet Union notes slightly fewer significant errors on the order of 5-25 mm (Yang et al., 2009). In-situ measurements tend to generate higher values than remote sensing estimates (Howell et al., 2012). These errors in passive microwave SWE estimates are quite significant given that area-averaged SWE values for some regions are quite low. The Yukon River Basin, for example, has an average SWE of ~90-100 mm during the winter season (Yang et al., 2009). For another comparison, errors of 5 to 40 mm correspond to vertical loads of approximately 0.049 kPa to 0.392 kPa; minimum snow load requirements for unexposed buildings in Whitehorse and Yellowknife areas are on the order of 1.54 kPa and 1.86 kPa, respectively (NRC, 2010).

The Yukon and NWT are located in a region in which Räisänen (2008) suggests would actually experience an *increase* in maximum SWE over the coming decades, due to the complimentary effects of warming and water vapour capacity discussed above. Western portions of the NWT are known to have above average snow densities, particularly the corridor from the western end of Great Slave Lake north to Tuktoyaktuk (Mekis and Brown, 2010). Neighbouring portions of Nunavut exhibit some of the highest average snow density values in the country, mainly attributed to rapid snowpack evolution under Arctic conditions.

In contrast to Räisänen (2008), Brown and Mote (2009) only found a robust increase in maximum SWE at higher altitudes, roughly in the range of 750 to 1100 m above sea level, with portions of the Yukon identified as being most sensitive to changes in climate (Brown and Mote, 2009). They describe how "at higher elevations, the snow cover is continuous, so [maximum snow water equivalent] can only respond to changes in snowfall amount" (Brown and Mote, 2009). Furthermore, individual model results ranged from 'no change' to significant increases in SWE in the Canadian Arctic; hence no GCM indicates a decrease in SWE for the region. This is again a case in which 'ground truth' observations and trends would need to be employed, rectifying conflicting model results. However, while Brown and Mote (2009) indicated that there was no additional evidence of SWE value increases in northern Canada[3], the Government of the Northwest Territories (GNWT, 2004a) has already taken action to address increasing snow loads on public buildings.

3.3.3. Snow Depth and Seasonal Accumulations

In terms of individual weather events, there is some evidence that the incidence of heavy snowfall may be increasing more quickly than light precipitation. This occurs due to the fact that some atmospheric processes are more sensitive to warming than others, meaning that changes in climatic drivers may have a more pronounced effect on some storm types. Stone et al. (2000) assessed daily precipitation data across Canada and separated them into three levels of intensity: light, intermediate and heavy. They found the most pronounced increases occurred in heavy winter precipitation events in northern regions of Canada, particularly in the three territories and the Arctic. None of the other precipitation trends approached the magnitude and statistical significance of the northern winter events. Also of note were decreases in the frequency of light precipitation events detected at some of the stations which showed increases in heavy events. However, nearly two decades have passed since the end of the period of record assessed by Stone et al. (2000)[4], and more recent work using updated data sets is needed to assess if these trends have continued.

In recent years, record snowfall amounts have been recorded in both the Yukon and NWT. The Yukon experienced record snowfall amounts in 2006-2007 (Keevil, 2008) and again in 2008-2009 (Munson, 2009a). Large portions of southern Yukon reported 2009 end-of-season (April 1) snow packs over 150% of normal values (Joe-Strack and Janowicz, 2009a-c). More recently, a number of locations in the southern NWT have been reporting record seasonal snow amounts (AANDC, 2013). These conditions are likely linked to incidents of snow load roof collapse and are currently raising concerns over the potential for flooding from snowmelt. Again, trend analyses in observational data need to be updated and attribution studies need to be conducted to determine if these records reflect natural variability or potential influences from teleconnections, or if they are indeed consistent with expected impacts from anthropogenic climate change.

When investigating regional and location-specific trends, results become significantly more variable. Janowicz (2010) provided a brief calculation of seasonal precipitation trends for several stations in the Yukon and adjacent regions, noting general increases in winter precipitation in northern regions but decreases in the southern regions. Shingle Point, at the northern tip of the territory, showed a very strong increase in winter precipitation, consistent with Stone et al. (2000); however, data are only available for 1957-1992. Inuvik, further to the east, showed a general decrease of a similar magnitude in winter precipitation for the 1957-2005 time period. Based on climate change projection results from the Canadian Regional Climate Model (CRCM, version 4), Werner et al. (2009) indicated that increases in winter precipitation may be greater in western portions of Yukon compared to the east. Hence, there is evidence for some important regional differences in snow behaviour, including apparent conflicts between observed trends and future projections. Particularly notable are the potential for decreases in winter precipitation in southern parts of Yukon (Janowicz, 2010), which merit further investigation.

3. However, they did cite proxy evidence in northern Quebec, with increased snowfall based on lake-level assessments and an analysis of black spruce growth forms (Brown and Mote, 2009, p. 2142).

4. Stone et al. (2000) also indicated that the majority of the increase in heavy precipitation events in the North appear to have occurred in the 1960s (see Figure 3, Stone et al., 2000); this is apparent as a steady increase to above-average values, but data in the 1990s also show a sharp increase beyond 1960s values as well as greater variability. Again, additional data for more recent time periods is needed to better characterize current trends.

In terms of hazards, snow accumulations generate both direct (e.g., road blockage, avalanche risk, infrastructure loading) and indirect (e.g., ground insulation effects) hazards for mining and transportation. Increases in snowfall in mountainous areas, such as large portions of the Yukon, would mean increases in avalanche hazards, including snow avalanches, debris falls and rock falls (Anisimov et al., 2007). Studies of snow depth, however, have only assessed trends in seasonal accumulations. In fact, Dyer and Mote (2006) found a decrease in average snow depth that began in mid-December along the Yukon-NWT border, spreading eastward and southward as the winter progressed. These studies do not tell us anything about extreme snowfall amounts for individual events or about the total amount of water represented by these snowpacks. Extreme precipitation events have shown increasing trends across North America (Kunkel et al., 1999), but aside from Stone et al. (2000), Zhang et al. (2000), and Kunkel (2003), studies of heavy and extreme snowfall events in northern Canada are lacking, particularly studies that include more recent climatic data.

In terms of direct impacts to water bodies and rivers, which are particularly relevant for mining activities, at least some river basins in Yukon may be experiencing thinner river ice due to increased snow cover (Janowicz, 2010). This will impact river ice breakup events and associated flooding. In fact, mid-winter breakup events have begun to occur for the first time on record at a few locations in Yukon (Janowicz, 2010).

3.3.4. Snowmelt and Spring Run-Off

Both SWE and SCE duration have important links to spring runoff amount and timing. Howell et al. (2012) conducted field studies of snow characteristics at Polar Bear Pass, Nunavut, documenting the dominant drivers controlling snow melt and runoff, as well as providing verification and comparison for satellite data and its ability to detect snow melt. Their results indicated that air temperature is indeed the key driver for snowmelt onset, suggesting that a warming climate could lead to earlier and faster snowmelt. They also noted that "...increased winter SWE values are not sufficient to retard the snowmelt season with increasing temperatures." (Howell et al., 2012), implying that hazards due to spring run-off will likely not be mitigated by the additional time required for melting more snow. Eurasian rivers have shown an increase in drainage into the Arctic Ocean since the 1930s; however, results for northern Canada and their links to changing snow characteristics, particularly the Mackenzie River, are somewhat more uncertain due to regulatory flow controls[5] (Anisimov et al., 2007).

Some have suggested that increased winter precipitation and snow retention should produce a signal in river flows. These have been detected, but detailed assessments of causal factors have shown that much more complex inputs than simply additional precipitation may be responsible (Anisimov et al., 2007). Brabets and Walvoord (2009) found that winter and average April flow rates throughout the Yukon River basin were increasing. Though the study was intended to investigate the impacts of the PDO on flow regime, they also noted statistically significant increases in the winter flow rate in the upper part of the basin (in Yukon and eastern Alaska) regardless of the PDO phase; this indicates a longer-term climate trend signature in addition to the PDO. These winter trends in increasing flow in cold-PDO years were not found for middle and lower basin sites in western and central Alaska. A similar study of winter river flow in the NWT found very large increases (up to 272%) in winter flow values, as well as what appears to be an emerging increase in total annual flow at some stations (St. Jacques and Sauchyn, 2009). Many of the annual flow increases have only recently (i.e., post 2005-2007) become statistically significant, which emphasizes the need to include the most recent data possible. Observed increases in the NWT were, on average, much larger than those observed in the Yukon study.

5. The Lena River in Russia, for example, has been shown to have undergone increased flow driven by precipitation increases (Anisimov et al., 2007).

Both studies suggested that the dominant mechanism consisted of increases in groundwater contributions due to permafrost thaw and increased active layer depth and water storage; however, they do not present precipitation data to determine if winter and early spring rainfall also play a role. However, Brabets and Walvoord (2009) also suggest that greater winter precipitation and snow retention in the interior of Alaska may be responsible for increases in April and May flows in the main basin as well as specific tributary basins. The upper Yukon River also shows negative trends in summer flow for both warm-PDO years and for the entire period of record, linked to earlier snowmelt and runoff and implicating an overall decrease in summer water availability (Brabets and Walvoord, 2009). This has important implications for mining operations.

Several cases in which excessive spring runoff has already impacted transportation and mining are discussed below. However, studies looking specifically at the impacts of SWE on spring runoff volumes in rivers have simply indicated an earlier snow melt, and some suggest greater year to year variability beginning in the mid-1990s (e.g., Pelly Crossing and Mayo areas; NCE, 2011a,b). Interestingly, Rick Janowicz, Manager of the Hydrology Section for the Yukon Department of Environment, has suggested that climate change has not resulted in greater snowmelt flooding events from increased precipitation, but has noted that warmer winters have resulted in a greater number of ice jam floods (Munson 2009a). In contrast, Brabets and Walvoord (2009) have suggested that increased river flows in some Yukon River tributaries may be due to increases in winter precipitation and subsequent flooding, indicating that impacts from changing winter precipitation will likely be region-specific. Climate change projections have consistently indicated an overall future increase in precipitation in Yukon (Zhang et al., 2001), but elements such as the snow-rain ratio and seasonal differences vary substantially.

3.3.5. Rain-on-Snow Events

Rain-on-snow events fall under the category of 'complex extremes' (Benestad and Haugen, 2007; Stephenson, 2008), in which the combination of more than one climate element results in potentially high impact consequences, even in cases where the values attained by those individual elements were below extreme values (e.g., moderate rain on moderate snowpack). Rain-on-snow events generate a flooding hazard and significant infrastructure and roof loads, as well as secondary impacts such as increasing susceptibility to pollution and acidity infiltration from enhanced runoff (Ye et al., 2008). Rain-on-snow events and cold season rainfall in general may also play a significant role in ice road season length (Rawlings et al., 2009), a link which has only recently been identified and merits further study.

Ye et al. (2008) studied rain-on-snow events in northern Eurasia. Their study indicated a very strong positive correlation (99% statistically significant at 18 of 22 stations studied) between increases in average annual temperatures and increases in rain-on-snow events, with increases of about 0.5 to 2.5 rain-on-snow days yr^{-1} for every degree Celsius. This occurred in conjunction with increases in the number of rain-only days, indicating that it was not simply a change from snow to rain. This correlation only appeared to reverse when mean winter temperatures for the station were above -8°C. This has obvious implications for Canada if a similar correlation holds for North America, given that most areas of the country fall well within this positive correlation zone. Ye et al. (2008) also noted that the strongest increases appear to occur in regions where such events had been rare in the past.

Although no published studies have been conducted for the Canadian Arctic and subarctic, anecdotal evidence and practitioner interviews for this project (E. Sparling, pers. comm., 2013; NCE, unpublished data, 2013) also indicate that rain-on-snow and winter rain events are potentially emerging hazards for northern regions of Canada as well.

3.3.6. *Local Studies: Comparison to Regional Trends and Projections*

A number of local studies have been conducted that attempt to define climate change implications for specific locations (e.g., Dawson City, Pelly Crossing and Mayo; Hennessey, et al., 2011, 2012; NCE, 2011a,b; Werner et al., 2009). These studies often exhibit the wide variety in differences between local and territorial or regional scale changes, as well as highlight some of the analytic difficulties related to data sparseness. For example, in the NCE reports on Pelly Crossing (2011a) and Mayo (2011b), data was used from the Mayo climate station to provide a baseline for comparison to climate change projections for both communities, even though Pelly Crossing is located nearly 95 km to the south of Mayo and located in a different river valley. The NCE climate adaptation report for Dawson City (Hennessey et al., 2011) employed climate change projections provided by the Pacific Climate Impacts Consortium (PCIC) (Werner et al., 2009). For the period 1955-2004, Dawson City exhibited a 31% per century decreasing trend in winter precipitation, while Pelly Ranch and Mayo, located roughly 160 and 170 km to the southeast, respectively, showed rates of 7% and 30% per century *increases* for the same period (Werner et al., 2009). Baseline values were then compared to CRCM Version 4 results as well as temperatures from an ensemble of 15 GCMs. Increases in precipitation were indicated across the region, although Werner et al. (2009) conceded that the CRCM and its parent GCM tended to be warmer and wetter than the average output from the ensemble.

Climate change projections in these studies are even more variable, and may not be directly comparable given differences in methodology and model selection (e.g., CGCM V.4 in Werner et al., 2009 versus SNAP in NCE, 2011a,b). However, there appears again to be a consistent increase in annual precipitation, with the summer months showing the smallest change, as well as greater increases in winter temperatures versus summer.

3.4. Changes in Snow

Climate change will likely lead to greater snowfall amounts and total equivalent water values in most regions, and result in significant implications for all associated hazards, although results for specific regions are still somewhat conflicting. This is further complicated in many regions, particularly in Yukon, due to complex topographical influences and strong regional contrasts in climate. Snow densities (e.g., those from new snowfall) are also highly dependent on the mechanism (e.g., storm type) producing the snow and attendant conditions. According to Mekis and Brown (2010), “the annual variability in the [snow water equivalent] depends on several factors including the number and type of winter storms.” While a detailed characterization of different snow storm types for the region is beyond the scope of this literature review, an assessment of this nature is suggested. This is important given the differences in how climate change is expected to impact different processes and that it will likely affect some storm types more than others.

It is becoming quite clear that many of the snow characteristics which will directly impact the built environment are not well observed, and that the components and factors which are better represented by climate change models and are more easily measured by remote sensing (e.g., SCE) cannot be used as substitutes for these measures. Apparently conflicting trends, with increases in heavy precipitation events and possibly SWE values, but decreases in depth and snow cover extent and duration, are indicators of significant changes in snow characteristics in the North. Coupled with recent impacts (e.g., roof collapse events, rain-on-snow floods) and the need for updated research (i.e., re-assessment of trends in precipitation intensity employing more recent data), there is a clear need for more continued research.

3.5. Mining Sector

3.5.1. Mine Hazards

The Suzuki Foundation funded the first study to look at climate change impacts and research on a national scale for Canada's mining sector (Pearce et al., 2009). This included a literature review of both industry publications and the scientific literature, as well as surveys of industry representatives and practitioners. Components of this research have since been published (e.g., Ford et al., 2010; Pearce et al., 2011) and are included in the discussion below. Their survey of mining industry representatives at the March 2008 Prospectors and Developers Association of Canada (PDAC) conference found that "snowfall was noted as the most common event affecting mine operations," as indicated by 55% of respondents. Research also indicated that mines relying on single access transportation infrastructure were the most vulnerable to climate change (Pearce et al., 2009), coincident with other studies which indicated that for northern mining, the loss of ice roads due to climate change was a particular concern (Prowse et al., 2009).

Permafrost can impact the mining sector during initial mineral exploration, during mine planning and operation, and after the expiration of a mine. Current and planned mining operations (e.g., activities and infrastructure) will be able to adapt to incremental environmental changes with changes in management strategies and modest capital investment (MEND, 2011).

Snow contributes to a number of hazards for northern mines, namely, hazards such as building/infrastructure loading, water balance/flooding, and those relating to ground insulation. These effects are important for both operational and abandoned/decommissioned mine sites, and Yukon is particularly vulnerable due to its century-long history of mining (MEND, 2009a; I. Church, pers. comm., 2013). Abandoned and decommissioned mines have been designed for past climatic loads. This means that they may be under-designed for future climatic values, and many have further suffered from a lack of maintenance since closure or abandonment (Pearce et al., 2009).

3.5.2. Exploration and Site Planning

Although there is a lack of literature regarding impacts of climate change on mineral exploration, warming permafrost may present both challenges and opportunities that vary spatially in intensity (Bond and Lipovsky, 2011; Prowse et al., 2009). Challenges for exploration may include the construction of infrastructure on warm, thawing permafrost; the availability of groundwater; the timing of exploration activities; and the cost and impact of drilling. Overall, the degradation of permafrost may be regarded as an opportunity for growth in regions where exploration was previously too costly or inaccessible (Prowse et al., 2009).

3.5.3. Infrastructure Design and Construction

Critical permafrost-related planning factors for a mine site include the spatial distribution and thickness of the frozen ground, the ground material and ice content, and the temperature of the permafrost both at depth and near the surface. Successful development of mining operations is only possible with a thorough understanding of these planning factors before construction (Bond and Lipovsky, 2011). To assess these correctly, monitoring of the climate and the ground (e.g., air and ground temperatures, active layer depth, and precipitation) should be conducted for at least three years prior to construction (EBA, 2004).

EBA (2004) highlights four approaches to the design of a mine in permafrost environments: remove all overburden and build on bedrock (even if frozen); strip vegetation and assume that permafrost will thaw (which may take several years); remove permafrost and replace with thaw-stable backfill materials if required (common if permafrost is thin); and, preserve the permafrost through various cooling methods (common if permafrost is thick). These considerations will be assessed for open-pit, underground and above-ground infrastructure.

3.5.3.1. Open-pit infrastructure

Open-pit mining is a mining technique that occurs at the surface of the earth when the desired resource occurs near the surface or in terrain that is unsuitable for tunneling. Mineral or rock resources extracted from open-pit mines include diamond, lead, zinc, copper, gold, and building materials from quarries.

The stability of steep bedrock slopes does not seem to have been very well investigated in permafrost environments. Freeze-thaw cycle penetration and intensity, hydrological changes, and extreme weather event frequency and intensity can all threaten slope stability (Gruber and Haeberli, 2007).

3.5.3.2. Underground infrastructure

Generally, underground mines are deep enough that permafrost is not a significant issue. Some concerns exist about drilling and excavating in permafrost terrain and the associated hydrological impacts on groundwater.

Ghoreishi-Madiseh et al. (2011) have modelled the thawing effect of backfilling mines with materials that are warmer than the surrounding bedrock and permafrost. Backfilling of a stope (an evacuated underground space) is done when subsurface mining operations are completed, in order to ensure long-term structural stability. Ghoreishi-Madiseh et al. (2011) used a heat transfer equation in a two-dimensional mathematical model that simulated a stope with a uniform boundary conditions relationship between the warmer backfill material and the frozen enclosure. They found that the initial temperature of the backfill influences the depth and permanence of the thaw radius. With a 5°C backfill, the thaw radius will completely disappear by day 120, though a 25°C backfill will stabilize at a 1 m thaw radius over the same time period. This means that given the right conditions, backfilling a stope could result in a thaw radius capable of destabilizing the stope.

3.5.3.3. Aboveground infrastructure

This report does not focus on building foundations and engineering best practices, although these remain an important factor to the mining sector in the North. EBA (2004) suggests a minimum of geotechnical information is necessary before constructing a building. This includes a visual assessment (i.e., in-situ, aerial, or other) of the potential for the presence of permafrost, slope instability and drainage issues, ground temperature data, knowledge of the ground ice content, active layer thickness, and lithology of subsurface materials. To evaluate ice content in fractures, the rock must be cored using chilled drilling fluid.

Placer mining takes place entirely above ground and represents a significant part of the mining industry in Yukon. Placer mining, especially in and around the region of Dawson, may occur in areas of permafrost. In these cases, a process of hydraulic mining is used whereby a powerful jet of water is used to thaw the frozen ground and carry the slurry of gold, sand and gravel to the sluice box where the gold is separated out (Water Resources Branch, 2011).

Climate change could have positive impacts on aboveground mining. A reduction in the extent of permafrost could facilitate the removal of overburden (Water Resources Branch, 2011), making the installation of above-ground infrastructure easier.

The Diavik diamond mine in Northwest Territories is actively freezing existing permafrost to prevent surrounding lake waters from inundating the mine. An incident at Red Dog mine in Alaska, where a miscalculation of permafrost led to the release of contaminated waters from its waste pond, ultimately resulting in the death of fish, motivated the search for new techniques for building in discontinuous permafrost zones (Haley et al., 2011).

3.5.3.4. Snow loading of structures

Sensitivity to snow loading varies between structures. The GNWT's *Roof Snow Overload Risk Estimation* guide (GNWT, 2004b) defines basic components which affect loading vulnerability, including roof shape and slope, construction material, building design, and maintenance history (e.g., age, water infiltration, renovation). The *Roof Inspection Checklist* (GNWT, 2004c) further aids in determining structural integrity when the details of the building's history is unknown. Snow drifting has also been a factor in roof collapses, and is often taken into account for maintenance decisions regarding snow removal.

3.5.3.5. Insulation effects

Snowfall has the secondary effect of insulating the ground, resulting in increased ground temperatures and surface ice temperatures (e.g., on lakes and rivers), as well as dampening the effects of air temperature changes on these surfaces. In mining, this effect is most detrimental to structures relying on permafrost for integrity (e.g., tailings dams and other containment structures, building foundations and supports). As well, there is a need to prevent chemical or biological activity in tailings containment facilities to reduce acid rock drainage (Kyhn and Elberling, 2001).

Early consideration of the local distribution and characteristics of permafrost during the closure of a mine can influence the tailings disposal methodology (EBA, 2004). Climate change impacts on the stability and effectiveness of post-closure infrastructure are of great concern (MEND, 2011). Permafrost offers an impermeable layer against downward movement of solutes. However, the near-surface containment of waste, either in the form of rock piles or tailings ponds, is often a heat sink that leads to the thermal degradation of permafrost.

3.5.4. Water and Tailings

Dams and dykes are often used to contain tailings ponds. Over time, these structures can deteriorate; in permafrost regions, differential thaw settlement and other factors can accelerate the deterioration in a warming climate. For more information of this topic, see reports by the Mine Environment Neutral Drainage Program (MEND, 2004, 2009a,b, 2011, 2012), the Mining Environment Research Group (EBA, 2004), Government of Nunavut (2012), and Bjelkevik (2005).

3.5.4.1. Acid drainage

Acid rock drainage (ARD), also known as Acid mine drainage (AMD), results from the natural oxidation of sulphide minerals in mining waste (Kuyucak, 1999). ARD is a significant challenge in the mining sector, as it can occur at both operational and decommissioned mines. ARD can impact surface water and groundwater due to its low pH (high acidity) and sulphate content. Keeping tailings frozen year-round may slow ARD and may only be practiced in cold climate regions (Kuyucak, 1999). Control strategies of ARD in permafrost regions include:

- **Freeze control:** Freezing tailings at the surface in continuous permafrost. This technique is also known as encapsulation. While common in the North, it is the most susceptible to failure due to thawing permafrost (MEND, 2004).
- **Climate control:** Cold climates slow the production of ARD (EBA, 2004).
- **Engineered dry cover:** Creating an impermeable layer that prevents the oxidation of the tailings, limits erosion, and provides a surface for vegetation to regrow (MEND, 2004). Engineered dry covers minimize the influx of water and limit the intake of oxygen.

- **Subaqueous disposal:** Disposal of tailings beneath water is very effective to prevent oxidation, though not applicable everywhere and there is potential for trace metals in the tailings to leach into the water column (EBA, 2004).
- **Blending and segregation:** Neutralizing acidity by blending alkaline material (EBA, 2004).
- **Collection and treatment:** Collecting and treating ARD (EBA, 2004).

The in-situ assessment of a 1.2 m granular insulation cover over a tailings storage facility was conducted in the continuous permafrost zone of Northern Quebec. This study demonstrated that the insulating cover did not protect the tailings from the freeze-thaw cycles, and that oxidation still occurred below 0°C (Coulombe et al., 2012).

Changes in the environmental parameters (e.g., temperature, precipitation, permafrost) that inform the design of key structures relevant to acid drainage (e.g., covers, dams, treatment systems, and other water management structures) will not change sufficiently to increase acid drainage or lead to significant changes in prevention strategies (MEND, 2011).

3.5.4.2. Arsenic trioxide – Frozen Block Method

The Giant Mine (NWT) produced 7.6 million ounces of gold between 1948 and 1999 (Galloway et al., 2012). The roasting process to release the gold resulted in the production of 237,000 tonnes of arsenic trioxide, a toxic dust that is currently being stored underground. The Government of Canada took over the management of this mine in 1999 when the original owners, Royal Oak Mines, went into receivership. The frozen block method was chosen as a long-term management technique for the arsenic trioxide; the cost of this project is estimated to be $200 million over ten years.

The Frozen Block method (Figure 6) involves three steps:

1. Drilling holes in the rock and under the stopes and chambers and circulating a super-cooled liquid through the pipe. This effectively freezes the rock and water beneath the underground containment site.
2. Drilling vertical holes alongside the underground stope and circulating a super-cooled liquid through the pipe. Steps (1) and (2) create a frozen cup-shaped container that prevents water circulation.
3. Water is then added to fill the container. The super-cooled liquid circulates until the entire contamination area is frozen, after which a passive grid of thermosyphons extracts heat from the ground and keeps the ground frozen (Figure 6). Monitoring of the site should continue indefinitely (INAC, 2007).

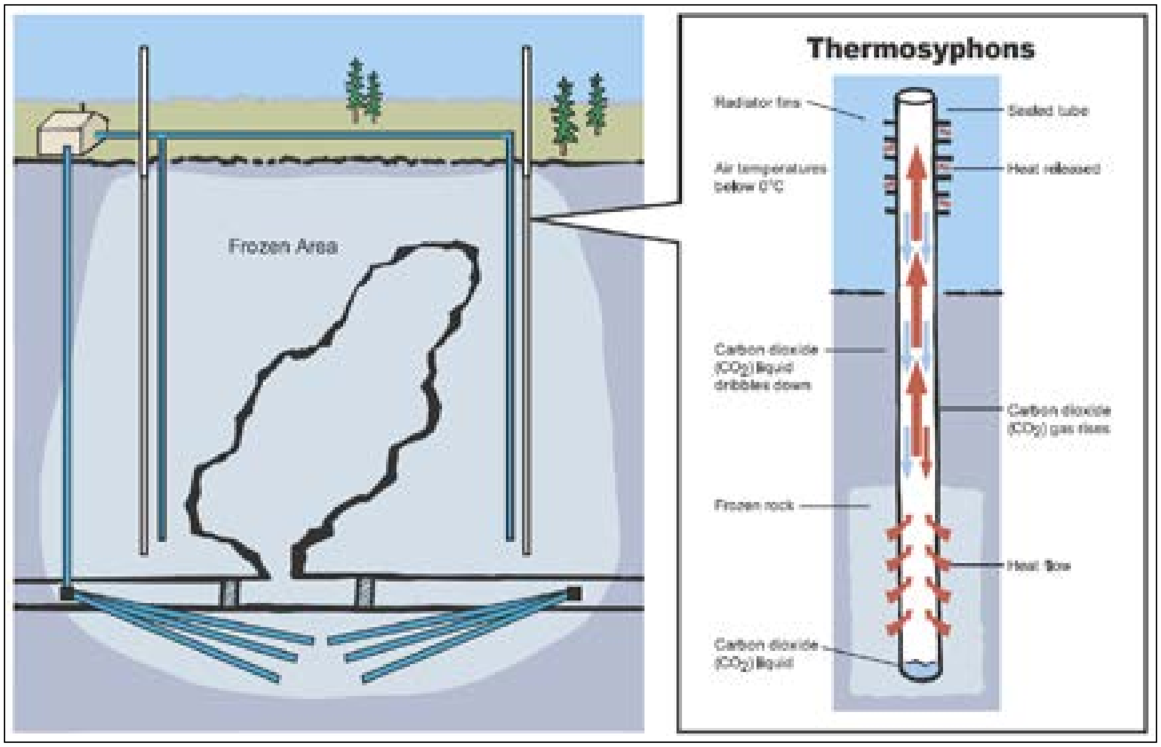

Figure 6. *The frozen block method uses thermosyphons to ensure subsurface contaminants remain frozen through time. This system is being used for the Giant Mine remediation project near Yellowknife, NWT (INAC, 2007).*

3.5.4.3. Waste water management

Mining activities generate waste water that requires treatment before reintroduction into the open environment. Efforts have been made to move towards passive techniques that treat water by natural wetland processing or atomization by snowmaking (EBA, 2004). By atomizing the nitrate solutes, they are distributed over the landscape in a similar way to the application of fertilizer (EBA, 2004).

3.5.5. Spring Runoff and Flooding

Spring runoff is often the dominant source of water in Arctic environments (Howell et al., 2012), either directly through seasonal snowmelt or indirectly through glacial melting and regeneration. Snowmelt is either a major contributor or the dominant mechanism responsible for flooding in the North (Pearce et al., 2009; Janowicz, 2010). Pearce et al. (2009) found that northern practitioners indicated a stronger survey response to flood hazards than their southern counterparts, suggesting that the spring freshet is indeed a significant hazard for northern mines. Flooding was also clearly emphasized in industry tailings management guidelines (MAC, 2011d) as discussed in detail below.

Flooding comes with a number of direct impacts: excess runoff erodes and weakens mine pit walls, exacerbates or induces acid rock drainage (I. Church, pers. comm., 2013), and undermines tailings containment structures. Combined snowmelt and rainfall can also overwhelm tailings facilities which were designed for single cause flooding (Pearce et al., 2011). Changes in northern water regimes are also expected to impact hydroelectric operations in northern Canada (Anisimov et al., 2007), many of which are essential to powering mining operations in remote areas (I. Church, pers. comm., 2013). Placer mining in particular is very water intensive, and 93%

of the reported water usage in the mining sector in Yukon comes from placer mining (Water Resources Branch, 2011). Therefore, changes in water regimes will have a disproportionate impact on those activities.

3.5.6. Avalanche Risks

Several mines have been identified as being located in high-risk avalanche zones, including two along the Yukon-NWT border, and two in the medium-risk zones in south-central Yukon (Campbell et al., 2008). It has also been suggested that increased avalanche risk is expected in the future, since resource extraction activities tend to occur in easily accessible locations first, followed by exploration of more remote areas, such as mountainous terrain, which are much more prone to avalanche risk (Campbell et al., 2008). While no avalanche fatalities associated with mining activities have been documented in Yukon or NWT (CAC, 2013), the risk has been clearly identified.

3.5.7. Site Accessibility

Snowfall impacts on site access are a significant, if not leading, issue for Canadian mines (Pearce et al., 2009), but important threshold values (e.g., depths) are difficult to find in the literature and may vary significantly depending on the operation or mining type in question. For some base metal mines (in contrast to high-value materials such as gold), year-round (all-season) roads may be necessary for the mine to remain profitable, presenting a significant challenge for long-distance transportation and road design in permafrost regions (McGregor et al., 2008). Fuel is the single most common item transported to mines due to the high fuel consumption needed for operations (Ford et al., 2010); therefore a loss of site access can lead directly to cessation of operations. Studies of extreme snowfall trends and threshold values for operations and transportation are therefore critical in understanding how snow may impact site accessibility. Examinations of climate-change projections and potential impacts on transportation indicate reduced access and longer surface travel times in most parts of Canada (Stephenson et al., 2011).

3.5.8. Implications for Mines

Increased snowfall amounts will exacerbate impacts from all hazards discussed above. For instance, even small increases in snowfall amounts produce significant insulation effects, with Kyhn and Elberling (2001) demonstrating that as little as 5 cm is enough to generate significant increases in tailings pond temperatures. The magnitude of the insulation effects also depend on the time of year and ambient air temperature during the first permanent snow fall (Kyhn and Elberling, 2001), both of which are expected to change due to climate change.

“Water and water related issues dominate mine development, operational… closure and abandonment considerations.” (I. Church, pers. comm., 2013) Increases in spring runoff may overwhelm tailings containment systems, leading to either failures or the need to release untreated water to prevent damage. Such releases have already occurred at the Minto Mine in Yukon in 2008 and 2009 (Thompson, 2009). Water is collected at some sites for later use (Pearce et al., 2011), and so changes in seasonality in snow retention amounts and melt timing, when combined with summer events, will affect water storage design needs. Increases in both extreme precipitation amounts and the length of precipitation-free periods between events, for example, will require greater capacity for water capture facilities to store precipitation when it occurs and also for retention during dry periods. Increases in SWE may not be enough to slow melt rates (Howell et al., 2012), and any increases in water accumulation will translate directly into higher water levels during spring runoff.

Increases in precipitation in some regions will result in snow load increases for buildings and infrastructure. Remote mining camp sites in Yukon and NWT encompass several hundred buildings, including administrative buildings and living quarters which shelter hundreds of workers at any given time. In 2010, nearly 53,000 Canadians were employed in Stage 1 (primary extraction) mining activities (MAC, 2011b); however the number of employees located in buildings in northern mines is difficult to determine[6]. Buildings at these sites will continue to become more vulnerable to increasing snow loads, an issue that has already been identified by engineering practitioners working in the North (E. Sparling, pers. comm., 2013). Modifications and maintenance actions have already taken place for government-owned buildings in NWT (GNWT, 2004a). These actions, coupled with snowfall amount and density monitoring, are needed for buildings at mine sites.

Table 1: Snow and permafrost hazards and sensitivities for mining.

Snow	Permafrost
overwhelming under-designed tailings facilities (overflow) or contributing to erosion (weakening containment); snow-melt induced flooding (Pearce et al., 2011)	permafrost thaw can lead to infrastructure challenges (Bond and Lipovsky, 2011)
avalanche risk to mine sites and transportation routes (Campbell et al., 2008)	freeze-thaw cycling can affect slope stability in permafrost environments (Gruber and Haeberli, 2007)
snow loading; buildings and other facilities (e.g., conveyor belts; Ford et al., 2010)	transportation challenges on mine roads due to permafrost thaw; difficulty building roads (McGregor et al., 2008)
access loss: depth, road washouts, reduced visibility in blowing/falling snow	deterioration of tailings dams and dykes (EBA, 2004)
ground insulation due to snow; impacts on structures relying on permafrost (e.g., tailings containment, building foundations), acid generation in tailings ponds through biological activity (Kyhn and Elberling, 2001)	impacts on management of Acid Rock Drainage; control strategies depend on climate (EBA, 2004)
failure of snow fences for tailings ponds (Kyhn and Elberling, 2001)	initiating permafrost degradation when backfilling stopes (Ghoreishi-Madiseh et al., 2011)

3.5.9. Policies, Guidelines and Best Practices

3.5.9.1. MAC Towards Sustainable Mining initiative

The Mining Association of Canada (MAC) has developed the Towards Sustainable Mining (TSM) initiative which includes the TSM framework, self-assessment tools for policy, and monitoring guidance for both tailings facilities (MAC, 2011a) and Energy Use and GHG Management (MAC, 2011b). These frameworks incorporate a graded system, from C to AAA, based on their level of performance within several sub-sectors; MAC members are encouraged to maintain a minimum grade of A across all performance measures. They provide further direction in the form of three guides focusing on tailings management. The first manual, *A Guide to Management of Tailings*

6. We know, for example, this includes ~850 aboriginal employees in NWT diamond mines alone (MAC, 2011b); however, many are open-pit operations, so the total number of employees under snow-load roof collapse risk is not known.

Facilities, was first published in 1998 (MAC, 2011c; updated), and was then followed by two additional companion guides, *Developing an Operation, Maintenance and Surveillance Manual for Tailings and Water Management Facilities* in 2003 (MAC, 2011d; updated) and *A Guide to Audit and Assessment of Tailings Facility Management* in 2011 (MAC, 2011e).

The TSM tailings facilities assessment method (MAC, 2011a) encourages every facility to develop its own site-specific Operations, Maintenance and Surveillance (OMS) manual. The guide for tailings OMS development (MAC, 2011d) was found to have the most relevant and thorough weather and climate content; however, climate change is not explicitly mentioned within this document.

Chapter 4 of the guide for developing an OMS Manual (MAC, 2011d; updated) specifies site characteristics that should be documented, as historical data, and monitored for operations[7], including basic climate components such as temperature, wind and precipitation. Chapter 4 also specifies that natural hazards for the site should be noted, including flood potential, which could affect tailings material transportation and deposition procedures, and other operations. Chapter 6 discusses weather events in terms of "event-driven maintenance," in which maintenance actions are triggered by an event or observed threshold value. Prioritization of risks and documentation of maintenance are also listed as important steps. Chapter 7 discusses surveillance needs and the uses for these observations, which include emergency planning and response. Therefore, to follow these guidelines, it is essential to have access to available climate and atmospheric hazards information.

Within the guide, there was a clear emphasis on rainfall, spring runoff, and flooding, which was mentioned several times in various phases of tailings facility development. The guide specifies that phases of decommissioning and closure must be part of the planning entailed in facilities management, although climate change assessment and impacts were not mentioned explicitly for these phases.

The other tailings management guides (MAC, 2011c,e) contain very little climate or weather-related guidance, but do refer to the consideration of climate change (e.g., "future scenario planning"; MAC, 2011c) not as a baseline requirement, but rather it is viewed as a potential step towards leadership, or results in an "above and beyond" status in tailings facilities management for mining. Within the mining industry, there appears to be a clear emphasis on the mitigation of GHG emissions, rather than development of adaptation design or management measures; this has also been indicated in other studies (Pearce et al., 2009). Industry documents relating to monitoring protocols and that contain explicit content in TSM guidance and management assessment tools, offer excellent potential platforms for the integration of climate change adaptation into mining management practices.

3.5.9.2. Mining drainage and abandonment and reclamation guidance

One participant[8] in the interview component of this project referred to issues of mine closure, abandonment, and remediation as the most important and climate-sensitive component of mining, due to the extreme costs involved in remediation and clean-up measures which often need to be absorbed by government funds (NCE, unpublished data, 2013). These have obvious links to climate and weather, given the need to plan for changing atmospheric conditions and their effects on closed and abandoned mine sites. Previously abandoned mines, having been designed for past climate conditions, may be sensitive to future conditions (Pearce et al., 2009).

7. This also implies that there may be proprietary meteorological data for remote mining locations that could be used to enhance the especially sparse observations currently available through other networks.

8. Name and affiliations of interview participants are kept confidential.

Currently operating and future mines now face the challenge of generating waste management and closure plans, which must take into account future conditions in perpetuity.

Specific guidance that addresses climate and weather impacts on mining drainage is currently available. The Mine Environment Neutral Drainage (MEND) program[9] generated a guide for better prediction and management of chemical drainage from mines, entitled *Prediction Manual for Drainage Chemistry from Sulphidic Geologic Materials* (MEND, 2009b). This guide was investigated for climate sensitive components. It specifically mentions future atmospheric conditions and flooding in dealing with post-closure uncertainty in mine drainage prediction. Practitioners are encouraged to consider the impacts of climate and weather on site drainage over all time scales, from discrete weather events to long-term climate change, mainly beginning with a sensitivity analysis.

> *Climate conditions will directly determine the volume and rates of condensation and incident precipitation and in conjunction with the site and project hydrology, the volume of and rates of surface runoff, near surface seepage and ground water. Whether the ground is saturated and/or frozen may also be an important factor in determining the amount of drainage that infiltrates versus runs off, especially during snow melt and large rain events. (MEND, 2009b, p. 5-48*)

The report also encourages a proactive, analysis-based, preventative approach to management, which is directly compatible with suggested climate change adaptive strategy development.

> *Recognising that a results-based*[10] *approach is prohibitively expensive and environmentally unacceptable, governments and industry now require proactive measures to prevent impacts from the drainage from sulphidic geologic materials. (MEND, 2009b, p.1-2)*

A number of cases have arisen in which mining companies either disappear or go bankrupt, leaving government (and by extension, taxpayers) to cover the costs of clean-up and remediation (MEND, 2009b). A number of examples are currently ongoing in the Canadian territories (e.g., Giant Mine, NWT; I. Church, pers. comm., 2013). Future drainage chemistry must be predicted for proper site management and prevention of unnecessary environmental damage. Oxidation and other weathering processes render generally insoluble sulphide species into chemicals which are more readily dissolved and transported by water, as well as generating acids which lower the pH and exacerbate a number of issues (e.g., accelerate weathering of adjacent materials; MEND, 2009b).

Monitoring of snow via snow courses and measurement of snow water content are described as part of regular drainage condition monitoring. While the report cautions that there will be a range of uncertainty in drainage prediction results, “the objective is to reduce the uncertainty regarding drainage chemistry to a level at which plans that will meet the environmental objectives can be designed and implemented.” (MEND, 2009b, p. 2-2) Similar statements can be made for any predictive requirements for subjects discussed here. Table 2, below, describes some of the climate and weather-sensitive components relating to drainage chemistry.

9. http://www.mend-nedem.org/default-e.aspx

10. In this case, the term “results based” refers to the reactive approach, i.e., taking management actions after problems have occurred.

Table 1: Climate and weather sensitivities for mine waste drainage. ***(Adapted from Chapters 3-7 of MEND (2009).)***

Climate/Weather Related	Climate/Weather Driven
forest fires, forest succession	individual climate events, seasonal and annual variability, and climate change; influencing drainage input, extreme runoff or timing of runoff, drought, local water tables
physical and chemical weathering	changes in local flora following closure
drainage properties (flooding or loss of water)	drainage occurs mainly during specific season (e.g., snow melt runoff, heavy rainfall, at certain temperatures), high or low flow conditions
erosion and sedimentation (e.g., high wind/water velocity)	'threshold' conditions generating mineral instability, changes in drainage chemistry and contaminant loading
movement of eroded particles by air or water	weathering of materials (e.g., freeze-thaw cycles and ice intrusion, thermal expansion and contraction)
external pH contributions from precipitation	evaporation and transpiration (e.g., wind, air exposure)
wind/water-borne sediment	incident precipitation and surface runoff
weathering and chemical processes from microbial action (affected by temperatures and pH; see also Kyhn and Elberling, 2001)	humidity and air permeability
sulphide reactions are exothermic, potentially impacting adjacent permafrost	temperature and barometric pressure difference between enclosed mine components and outside
previous disturbances such as glaciation or fire	

3.5.10. Adaptation Tools for Mines

3.5.10.1. Snow removal

Snow removal is the main course of action for snow-hazard mitigation at mine sites. As discussed in the OMS guidelines (MAC, 2011d), site-specific thresholds for operations must be determined in order to decide which thresholds for snowfall amounts will trigger snow removal. This will also depend on the facilities in question; snow depth thresholds on roads which impede traffic and vehicle operations will be different than values required for snow removal from roofs or outdoor conveyor belts to prevent damage to these components. Examples of snow depth thresholds for mining are given in Table 3.

3.5.10.2. Snow fences and pond covers

Insulation from snow cover is also a significant problem for mine tailings containment in the North. To help reduce or prevent acid rock drainage, some tailings are kept at sub-freezing temperatures to prevent the oxidation of tailings material. However, ambient temperatures and/or insulation from snow cover can act to warm tailings material and allow microbial activity, and therefore oxidation, to occur (Kyhn and Elberling, 2001). Covers made of shale or other material are added to tailings containment ponds to maintain cold temperatures to prevent ARD, but these are rendered less effective with snow insulation.

Table 3. Examples of important weather and climate thresholds for mining.

Threshold	Impact
tailings temperatures: -5°C or above	sulfide oxidation by biological activity begins; up to 20% maximum rate at 0°C (Kyhn and Elberling, 2001); AMD generation
snow cover depth on tailings ponds: 5 cm	severely dampens cooling of tailings, insulation significant; greater depths do not result in significantly greater effects (Kyhn and Elberling, 2001)
snow depth restricting transport and operations	no threshold values found, though snowfall indicated as the most significant problem for mining operations (Pearce et al., 2009)
avalanche risk (high): mountainous terrain, average maximum snow depth >100 cm	regional threshold used by Campbell et al. (2008); site specific risk is dependent on site geography

3.6. Ground-based Transportation Sector

3.6.1. Road Hazards

3.6.1.1. Reduced visibility

Snow-induced hazards to surface transportation include reduced visibility due to blowing snow, and the Canadian Arctic has been long established as having the highest frequency of blowing snow events in the country (Phillips, 1990). High winds are capable of generating significantly reduced visibilities from blowing snow, resulting in dangerous road conditions even in the absence of concurrent snowfall. Blowing snow also produces drifting, which can cause further maintenance problems (e.g., ground insulation with impacts on permafrost on road embankments) and can also exacerbate snow loading on roofs of building (GNWT, 2004a).

Given the likelihood of greater precipitation accumulation in the region due climate change (Brown and Mote, 2009) and heavy precipitation events during the winter months (Stone et al., 2000), the number of snowfall events generating reduced visibilities may also increase. "[Snow] cover response to global warming is complicated by projected increases in precipitation, particularly over high latitudes… with potential for increased accumulation in high latitudes." (Brown and Mote, 2009)

Conditions which produce blowing snow are dependent on fairly complex factors, particularly at lower wind speeds. These factors include snow characteristics, such as particle shape, which are not usually known to forecasters (Baggaley and Hanesiak, 2005; Huang et al., 2008). However, fairly simple methods have been developed to predict the occurrence of blowing snow which could be applied to transportation needs.

Reduced visibility due to falling snow is equally complex, and studies of actual snowfall rates (based on water equivalent per hour) can vary significantly even in similar visibility conditions. Rasmussen et al. (1999) provide examples in which snowfall rates were all within the 2.0 to 2.5 mm hr^{-1} (water equivalent) range but resulted in visibility restrictions ranging from 3.0 km down to 0.38 km. In both blowing and falling snow conditions, visibility reduction is worse during daylight than at night, where visibility increases by a factor of 2 or more under the same conditions (Rasmussen et al., 1999; Huang et al., 2008).

3.6.1.2. Road closures

Loss of access to sites with single transportation route access was indicated as the greatest climate change vulnerability for mine sites (Pearce et al., 2011); prime examples of this vulnerability were documented at the Diavik Mine in NWT (Mesher et al., 2008) and the CanTung Mine in Yukon (CMJ, 2012a,b). Any number or combination of snow-related hazards could be responsible for road closures, including washouts, accelerated erosion due to spring runoff, excessive snow accumulations, and loss of visibility due to blowing snow or heavy snowfall. Given the likely increase in precipitation accumulation in the region (Räisänen, 2008), as well as trends in heavy winter precipitation events (Stone et al., 2000), more road blockages and mining operation delays are possible due to snow-related hazards (i.e., either on-site or site access problems).

3.6.2. Winter Roads: Compacted Snow and Ice Bridges

Snow produces a number of indirect impacts on winter roads. Deep snow cover early in the season can delay ice growth, leading to delay of road openings and load restrictions on ice bridges (Prowse et al., 2009). These roads also tend to be several hundred kilometres in length, with large distances between populated areas, allowing for significant changes in weather conditions along routes, between destinations, or during extended periods of travel. This is an established travellers' perception problem which Grant and Morrison (2006) termed the separation of "here" and "there"; though conditions may currently be favourable at both departure and destination points, there may be hazardous weather along the route or conditions may change during the time needed to travel. For example, during March of 2012, four vehicles were stranded overnight on an ice road in the Wekweeti area, and RCMP searchers were forced to stop overnight due to deteriorating road conditions (CBC, 2012c).

Snow impacts on winter roads may not be as simple as the insulation effects discussed in other studies (Stephenson et al., 2011). Season length may be affected by the interaction of snow with other elements such as rainfall, particularly at the beginning or end of the season. This appears to play a dominant role in determining beginning and end dates of operation of ice roads (Rawlings et al., 2009).

3.6.2.1. Avalanche risk

The avalanche risk to transportation routes is most pronounced in Yukon, where the majority of its highway system is located within moderate to- high-risk avalanche zones (Campbell et al., 2008). A significant portion of southeastern Yukon and southwestern NWT are located within a large high-risk area, and important Yukon roads and highways – specifically the Nahanni Range Road and large sections of the Robert Campbell Highway and Canol Road – are featured prominently in this risk area. The Haines road, south of Haines Junction in southwestern Yukon, is also located in a high-risk avalanche zone (Campbell et al., 2008).

3.7. Transportation Design, Construction, Maintenance and Operations

3.7.1. Thaw the Roadbed

One approach to building roads on permafrost involves thawing the roadbed before construction. This approach is most efficient when the permafrost is thin and thaw-sensitive. One of the advantages of this approach is that the permafrost will be completely thawed. The thawing of the roadbed can occur before construction or can be controlled during the operation of a road.

Pre-construction thawing of the roadbed can be done by removing the topsoil and vegetation, leaving the thin permafrost exposed and without insulation. This method may take multiple thaw seasons to complete, or it can be accelerated by adding dark material to the exposed ground surface in order for the ground surface to absorb incoming solar radiation (Regehr et al., 2012). The effectiveness and speed of this strategy is difficult to model and predict (Beaulac and Doré, 2006).

Post-construction controlled thaw can include widening of embankments to enlarge the disturbed area and thaw zone in order to help prevent failure of the structural core. Frequent snow removal will slow the thaw by removing the insulating layer. Failures should still be expected on the outer edges of the embankment (Regehr et al., 2012).

Some permafrost issues can be managed by appropriately choosing to undertake construction in either the winter or the summer (TAC, 2010). If winter construction is feasible, some advantages include: increased accessibility of the terrain using winter roads; building on a frozen active layer which provides a stable platform; simplified installation of culverts when there is no flowing water; and excavations that remain frozen and are more easily handled (TAC, 2010). Summer construction also has advantages, such as: the ability to compact granular fills; the capability to work and stockpile natural granular deposits; and finally, the construction performed during the summer has the benefit of preferable conditions with respect to longer daylight hours and more moderate working temperatures (TAC, 2010).

3.7.2. Cool the Roadbed

In order to achieve the long-term thermal stability of roadbeds underlain by permafrost, a number of construction techniques have been developed in various regions of the world. Each technique has advantages and disadvantages which are mostly related to the cost, effectiveness, and logistics associated with construction and maintenance.

Snowsheds and sunsheds have been shown to reduce mean annual ground temperatures by between 1.5 and 6°C. This change occurs by shading the road from solar radiation during the summer, by preventing snow cover from insulating the ground in winter, and by enabling air convection at the ground surface all year (Regehr et al., 2012). These awnings are often built as half-metre tall, wood-framed structures which are open on all sides and covered by sheet-metal roofing (Reimchen et al., 2009; Figure 7). These structures are susceptible to damage by wind, vandalism, car accidents, falling trees, among others. The cooling effect of snowsheds and sunsheds can be detected immediately (Lepage et al., 2012). Snowsheds and sunsheds have performed well in both Alaska and China; however, high-maintenance costs, a lack of durability, and hazards related to vehicle accidents are discouraging for large-scale implementation (Beaulac and Doré, 2006).

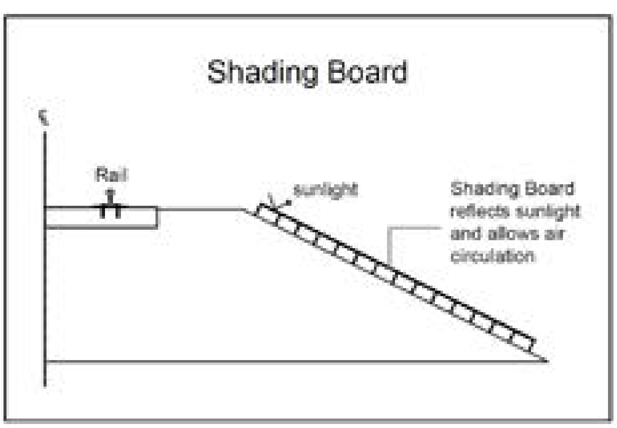

Figure 7. *Conceptual diagram of shading board (Regehr et al., 2012).*

Using reflective surfaces or light-coloured paint on road surfaces in order to increase the amount of reflected solar radiation has been shown to reduce heat transfer to the underlying subgrade (ADOTPF, 1985; Beaulac and Doré, 2006; TAC, 2010). The reduction of absorbed incoming solar radiation also reduces active layer depth (Regehr et al., 2012). The disadvantages of this strategy include the high costs of annually repainting the road surface due to weathering, as well as a number of associated hazardous driving conditions such as slippery road surfaces when wet, blinding driving conditions when the sun is reflected, and local icing at the surface (Beaulac and Doré, 2006; TAC, 2010). Jørgensen and Andreasen (2007) have shown impressive results of an overall reduction in the active layer thickness by 0.75 m beneath a 27 m-long test section of

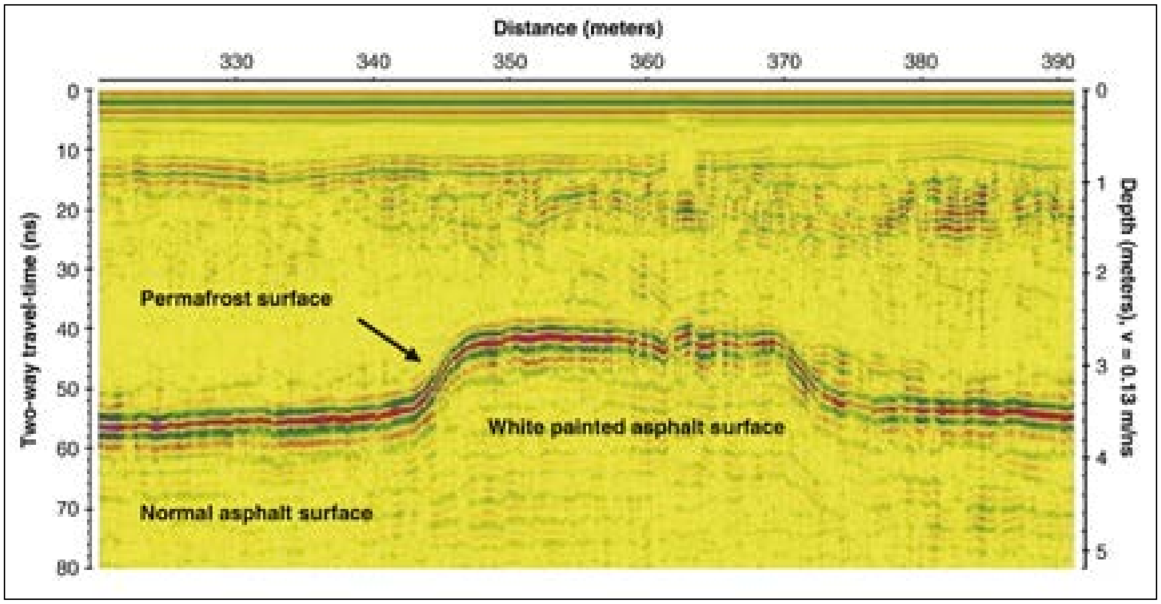

Figure 8. *Radargram of Ground Penetrating Radar (GPR) (Jørgensen and Andreasen, 2007).*

white asphalt at the Kangerlussuaq Airport, western Greenland (Figure 8).

Similarly, vegetation on the embankment of a road cools the ground by reducing solar radiation received at the ground surface (Regehr et al., 2012). Different types of vegetation will cool the ground to different degrees. Reimchen et al. (2009) highlight that grass-covered embankments may not be a viable solution in areas where there is a lack of suitable soil. Vegetation is often destroyed in the construction stages and may take multiple growing seasons to return. This is a low-cost method that has not yet proven to be highly effective or efficient (Lepage and Doré, 2010).

The air convection embankment (ACE) is a permafrost protection technique developed by D.J. Goering at the University Alaska Fairbanks (Goering, 1998; Goering and Kumar, 1996; Goering, 2003). ACEs enable heat extraction from the ground by creating convective cells for air circulation within the embankment. They are constructed with coarse-grained angular interlocking rocks ranging from 150 to 300 mm in diameter (TAC, 2010; Lepage and Doré, 2010). Air within the porous embankment cools near the surface in winter and sinks to the bottom of the embankment due to its higher density. The warmer air from the bottom then moves upwards, transporting heat toward the embankment surface. During summer, the convective flow stops because warm air stays at the surface of the porous layer, which acts as an insulation layer (Regehr et al., 2012). ACEs increase wintertime cooling and decrease summertime warming

(TAC, 2010). This technique is susceptible to intrusion of fine particles, snow, and water (Lepage and Doré, 2010). To prevent these intrusions, geotextiles should be placed on top of the embankment (TAC, 2010). Various designs of ACEs are shown in Figure 9.

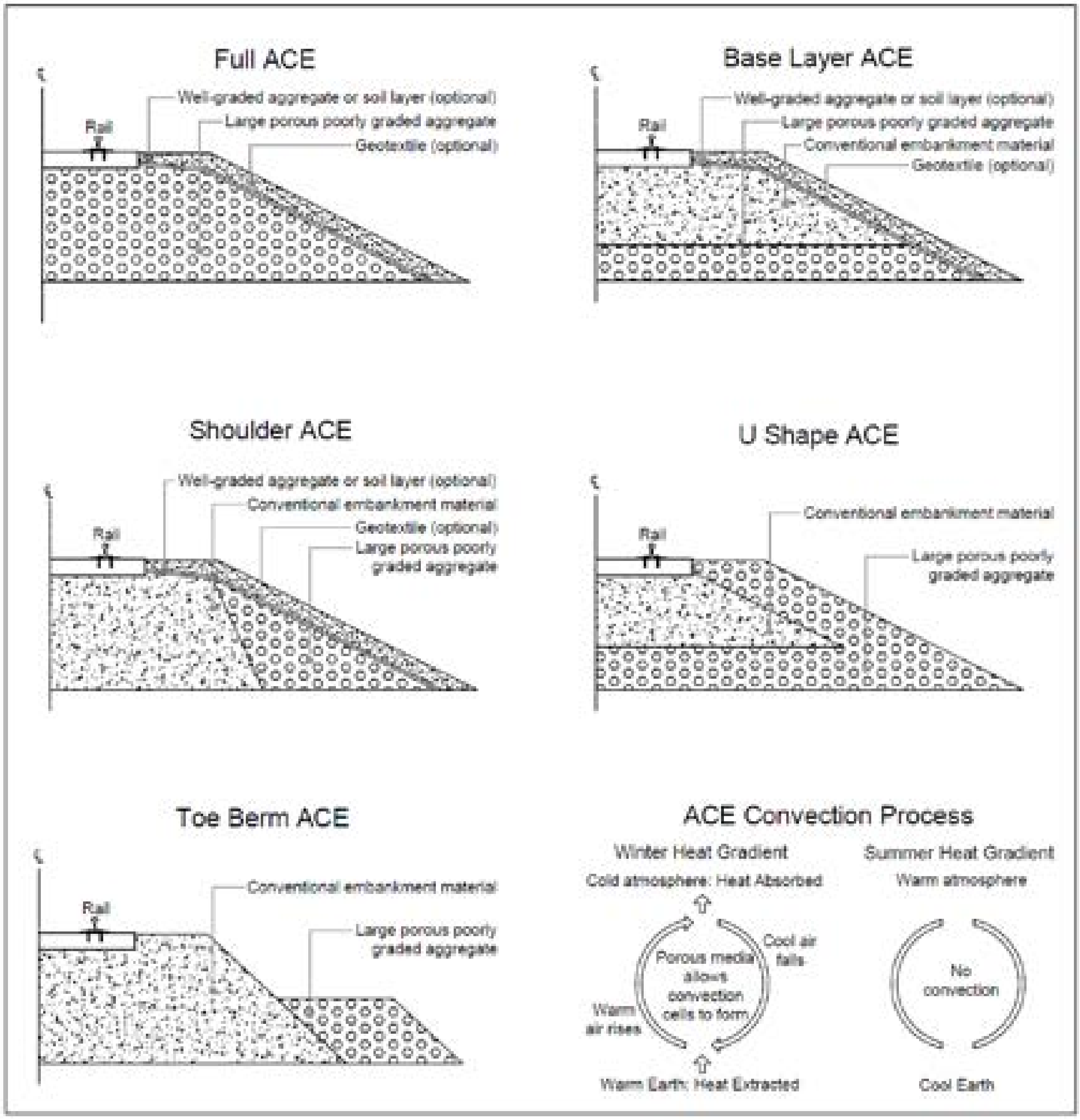

Figure 9. *Variations on the air convection embankment (ACE) design configurations (Regehr et al., 2012).*

North America is not alone in the struggle to build long-lasting infrastructure that retains structural integrity under changing permafrost conditions. Notably, technological advances have been made in China, where a large portion of the country is underlain by permafrost (Jin et al., 2013). A test section of hollow concrete brick revetment (concrete cylinders that line a road embankment) was completed in August 2009. The section is 30 m long, 7 m wide, and 3 m high. There are two layers of hollow concrete on both the sunny and shady embankments. These concrete pieces are hollow tubes with diameters of 15 cm (outer) and 10 cm (inner). The ice content beneath the road exceeds 70% and thickness is 1 to 5 m near the permafrost table. The results of the application of hollow concrete brick revetment are monitored from temperature readings; these readings are then compared to temperature readings from a similar site (100 m away) that does not have the new technology in place. The mean annual ground temperature (at 0.5 m depth) is on average 1-2°C cooler at the revetment site. The revetment serves as a sun shield and has complex internal air flow, thus, the more layers of concrete, the greater the cooling effect. Jin et al. (2013) may have found a cheap and viable technology to cool the ground beneath road embankments; the net effect of this is that the ground will remain frozen, potentially avoiding subsidence.

Ventilation ducts are large pipes that infiltrate the embankment and that enable cool, ambient air to pass beneath the road in winter, allowing heat from the ground to be released (Figure 10; Regehr et al., 2012). These ducts must be shut in summer to prevent warming of the permafrost from warm air circulating through the ducts. Both perforations of the horizontal ducts and the construction of chimneys enhance cooling of the ground. Ducts should be built on slight angles

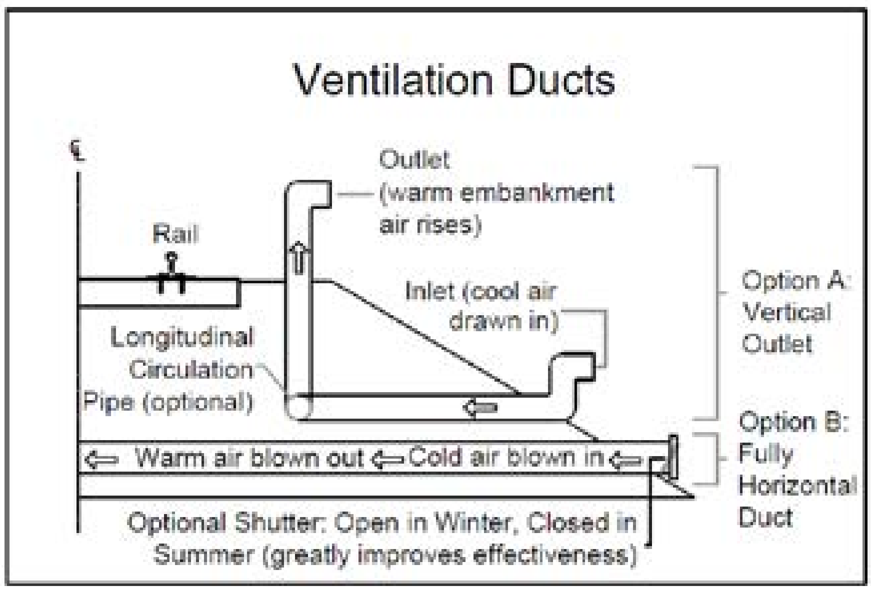

Figure 10. *Ventilation duct design (Regehr et al., 2012).*

to prevent pooling of springtime melt of windblown snow intrusions (Beaulac and Doré, 2006).

Thermosyphons are highly effective passive cooling mechanisms for preserving permafrost beneath building foundations; see Figure 11 (Regehr et al., 2012; TAC, 2010). They are not particularly well suited to the preservation of permafrost along roadways due to the high cost per unit and localized effectiveness (Regehr et al., 2012). These could be well suited on short sections of roads or airstrips that are located on thaw-sensitive permafrost (TAC, 2010). In addition, thermosyphons are vulnerable to damage from vehicle collision or vandalism (TAC, 2010).

Heat drains enable cool, outside air to pass through the embankment and for internal heat to be released. Results have shown that heat drains are successful at cooling embankments, though not as effective as ACEs (Regehr et al., 2012). Heat drains consist of a highly permeable geocomposite membrane of corrugated plastic wrapped by geotextiles (Lepage and Doré, 2010) that have an air intake at the foot of the embankment (Figure 12). Heat drains have been shown to cool the ground between 5 and 7°C (TAC, 2010). The main advantage of heat drains is that they are simple and relatively easy to install (TAC, 2010).

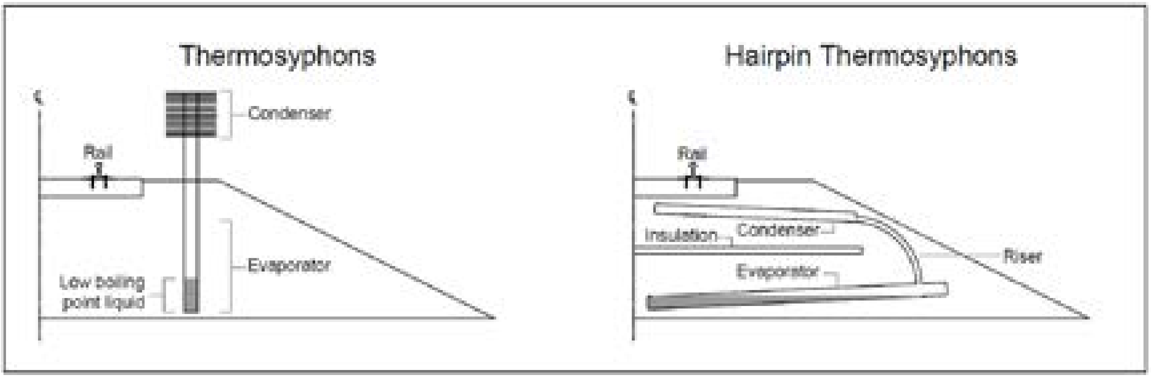

Figure 11. *Thermosyphon designs (Regehr et al., 2012).*

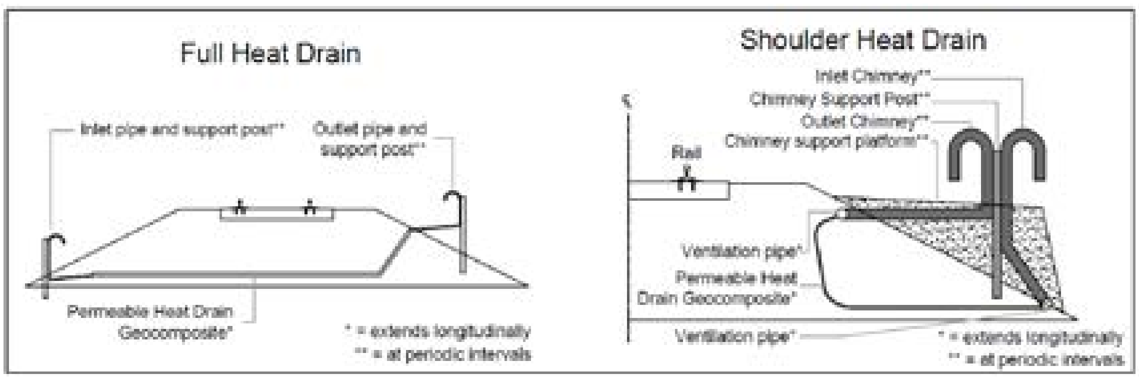

Figure 12. *Heat drains (Regehr et al., 2012).*

The dry bridge strategy consists of constructing a bridge over dry land; this is highly effective and extremely costly. The bridge enables cold air to circulate beneath the road (or bridge), reduces snow cover, and provides shade (Wei et al., 2009; Regehr et al., 2012).

3.7.3. Insulate the Roadbed

During construction of a roadbed or embankment, insulation can easily be installed beneath the ground surface and has been shown to mitigate thaw (TAC, 2010). The two materials typically used are polystyrene (foam boards) and polyurethane (foamed in place) (Regehr et al., 2012). Insulation protects permafrost because it impedes the downward penetration of heat into the ground during summer; however, insulation also prevents heat from escaping the ground in winter. It is important to note that insulation reduces the amplitude of air temperature variations but it only serves to delay thaw and does not reverse it. This strategy may be more effective in areas of cold permafrost rather than warm permafrost, as the winter ‘warming’ effect could potentially thaw permafrost if it is near 0°C (Regehr et al., 2012). The insulating layer has several important properties: it is a good thermal barrier, it has a low moisture absorption rate, and it is rigid enough to support the anticipated load (Holubec, 2008). The insulating layer is most effective when installed close to the surface, but the ground above must be thick enough to prevent crushing of the insulation (Beaulac and Doré, 2006). The advantage of using polyurethane is that shipping costs are reduced by foaming on site (TAC, 2010).

3.7.4. Strengthen the Roadbed

During construction, strengthening a weak subgrade soil with a stabilizing agent such as concrete, lime or bitumen may be appropriate (TAC, 2010). This technique may be the most appropriate if granular or quarry materials are not available. The stabilizing agent will increase the strength and reduce the permeability and frost susceptibility of the roadbed (TAC, 2010). When working with sand, stabilization techniques utilizing a combination of synthetic fluid and long discrete geofibers have been shown to be effective. Laboratory tests have shown that geofiber and synthetic fluid can significantly increase the bearing capacity and strength of silty sand (TAC, 2010).

3.7.5. Road Maintenance

In terms of hazards for roads, there are several important thresholds (Table 4). Snowfall is an immediate concern mainly for maintenance personnel (Cousineau, G., pers. comm., 2013). For paved road surfaces, bonding between the road surface and snow may occur, making snow significantly more difficult to remove. Anticipation of snowfall allows for preventative maintenance measures such as pre-wetting, early application of de-icing agents, and early mobilization of snow removal equipment (Smithson, 2004). In permafrost regions, snow removal from road surfaces and embankments as part of regular maintenance also serves to address the insulating effect that snow has on near-surface permafrost, thus preventing premature thaw.

Authors McGregor et al. (2008) and Mesher et al., (2008) reported on the design and assessment of two major NWT highway projects, the Yellowknife Highway (Highway 3) reconstruction and the Tibbitt to Contwoyto winter road, for which climate-change impacts were considered. In the case of Highway 3, the extension was simply designed to reduce climate-change impacts, i.e., by providing sufficient slopes to reduce drifting along the road edge and prevent insulation effects. With the Tibbitt to Contwoyto winter road, the focus was to consider optimising a shorter operating season and, more drastically, to relocate large portions of the road onto more reliable surfaces. Ideally, the entire southern 170-km section would be shifted from mainly ice bridge to compacted snow surfaces, increasing the operating season by approximately 30 days.

Another adaptation strategy for winter roads is improved maintenance. Some modified maintenance measures are already proving effective, since at least one NWT ice road has reported a statistically significant increase in season length; it was found that operational factors were a likely contributing factor, rather than purely climatic factors (Rawlings et al., 2009). Operational measures for ice roads include snow removal, spraying or flooding of ice surfaces for thickening, ploughing of ice surface to increase thickness, and operating at night to allow greater loads and increase transportation efficiency (Rawlings et al., 2009; Braden, 2012). In an interview with the Canadian Mining Journal, Tibbitt to Contwoyto road supervisor Kirk Keller made statements supporting this possibility, noting that snow clearing and flooding operations, which are intended to thicken ice as early and quickly as possible, have become a main priority in recent decades to allow for the greatest bearing capacity to be achieved (Braden, 2012). This may be an important factor in the road's ability to keep pace with increasing demand in spite of the changing climatic conditions.

The TAC (2010) guidelines recommend the following practices for road maintenance in permafrost regions:

1. Budget for maintenance activities.
2. Remain vigilant in managing performance risk.
3. Implement a simple monitoring program.
4. Increase the width of snow clearing to minimize the insulating effects.

5. Proactive measures should be considered for preventing icings, such as ice fences, frost belts, insulated subsurface drains, interceptor subsurface drains, or other methods.
6. Cover culverts that are not in active streams at the onset of winter to prevent plugging by snow and ice, and uncover them at the start of snowmelt to provide unimpeded drainage.
7. Identify the priority locations that would most benefit from technologies such as thermosyphons and develop an efficient means of installation.
8. Avoid delays in addressing minor incidents of ponding water.
9. Avoid opening new borrow sources when existing sources can satisfy the material quantities and type for construction.
10. Consider the overall drainage system when conducting maintenance as opposed to doing isolated activities such as installing or replacing culverts and deepening ditches, which could worsen problems like frost heave, settlement, embankment erosion and surface cracking.

Table 4. Important thresholds for roads.

Infrastructure	Parameters	Reference
ice bridges	0.7 m average thickness to open, 1.5 m for full traffic load	Nima et al. (2006); Mesher et al. (2008)
road closures	snow depth and/or reduced visibility	
design flows for culverts, bridge abutments, etc.	rain-on-snow, spring runoff, etc.	
snow loading, buildings and infrastructure	density, depth, additional rainfall	National Building Code 2010 (NRC, 2010)

3.7.6. Implications for Transportation

McGregor et al. (2008) defined four main categories of climate-change impacts for surface transportation in the North: increased costs (e.g., construction and maintenance); decreased ability to maintain an “acceptable level of service”; increased need for vigilance in maintenance and safety; and decreased overall transportation efficiency. Thinner ice on lakes and rivers, for example, leads to greater risks to drivers. Companies take on considerable risk with operations on ice roads in warmer temperatures, with an average of one fatality per year reported in western Canada from ice road failures (McGregor et al., 2008).

Impacts on winter roads are particularly important in NWT, although there are a small number of important routes in Yukon which also rely on ice bridges during the cold season. Approximately one third of all communities in NWT and all three diamond mines rely on ice roads as their main supply routes, and only 19% of the population of NWT has access to all-weather roads (Milligan and Montufar, 2011). The diamond industry has been responsible for roughly 50% of the GDP of NWT in recent years (Pearce et al., 2011). The three diamond mines located in NWT supply approximately 18% of the global market value for gem-quality diamonds, and traffic along the route could continue to rise with the potential opening of additional mines in the near future (Braden, 2012). The Tibbitt to Contwoyto winter road, which is the only supply route for the diamond mines, is the longest ‘heavy haul’ ice road in existence (Mesher et al., 2008), and is also likely the most heavily used transportation line in the world which is ice-reliant (McGregor et al., 2008). With such a significant dependency on ice roads, the vulnerability of the region's transportation sector is indisputable.

Restricted operating seasons for winter roads mean greater vulnerability to delays or closures from severe weather events. Regardless of the cause, these closures can become immensely costly given the limited time window for operation. For example, the Tibbitt to Contwoyto ice highway operates for roughly 65 days per year (2008 values), a number which is expected to decline to ~54 days per year by 2020 (McGregor et al., 2008). The 2006-2007 season, which saw an operational season of only ~50 days and a failure to reach full load-bearing capacity (Mesher et al., 2008), may well become commonplace in the near future. During that season, 15 million litres of fuel had to be flown into the Diavik diamond mine (CMJ, 2006), an expensive measure which cannot be sustained on an annual basis. Every day that a portion of the road is impassible represents approximately 1.5% of the entire operating season; with projections of a shorter season length in the near-future, this value approaches 2%.

The results of Stephenson et al. (2011) confirm the overall implications of climate-change impacts on surface transportation and winter roads. Employing a combination of climate and transportation models, this study, indicates that the amount of land area that is accessible by winter road in the Arctic is expected to decrease significantly, ranging from an 11% decrease in Greenland to 13% in Canada and as high as 82% in Iceland)[11]. Modelled losses were mainly driven by milder temperatures and greater snow depths, with the latter playing a role in permafrost degradation from ground insulation. They also cautioned that assessment of the complex interaction between climate and transportation systems requires careful consideration. They note, "our discovery of a strongly bimodal transportation outcome - improving access by sea but declining access by land - underscores not only the acute biophysical sensitivity of the Arctic to climate change, but also the inherent dangers of simplified characterizations of social response." (Stephenson et al., 2011, p.4)

3.7.7. Policies, Guidelines, and Best Practices

3.7.7.1. Guidelines

The Transportation Association of Canada (TAC) provides two guides which are particularly relevant to Yukon and NWT, entitled *Guidelines for Construction and Operation of Winter Roads* (PTM-COWINDRD-E, TAC, 2011) and *Guidelines for development and maintenance of transportation infrastructure in permafrost regions* (PTM-PERMAFROST, TAC, 2010). Both guides contain chapters on climate change.

8.1.4.1. Industry research

There has been a significant amount of climate change-impacts research carried out by the transportation industry in Canada, including work which specifically addresses issues concerning the North. For example, the chapters on climate change in the guides for winter road and permafrost regions discussed above (TAC, 2010; TAC, 2011), are in part the results of the TAC Climate Change Task Force, composed of a group of experts from across Canada whose focus is to conduct research on both mitigation and adaptation strategies for transportation (Cousineau, G., pers. comm., 2013; TAC, 2012; TAC, 2013). The Climate Change Task Force is currently collecting and compiling relevant information related to climate change and transportation, as well as identifying available tools and gaps with similar goals to this Cryosphere project, but under a national scope. For more than a decade, many of the annual TAC conferences have had

11. These values included all of Canada, since the study assessed all areas of North America north of 40°N.

climate change sessions, where several of the papers discussed in this report were presented (including Crowder et al., 2008, Mesher et al., 2008, Rawlings et al., 2009).

3.7.7.2. Monitoring, planning and forecasting

Permafrost maps do not yet exist at a scale that is relevant for assessing infrastructure hazards and the impacts of climate change and disturbance on permafrost (Trochim and Lipovsky, 2005). The Yukon Geological Survey, in collaboration with the Yukon Department of Highways and Public Works, has however compiled a database of borehole information (stratigraphy, texture, and ice character and content) from more than 4000 locations along the Alaska Highway and proposed pipeline routes (YGS, 2009). This approach to data organization is expected to improve spatial mapping of permafrost (e.g., depth, thickness, ice content) and improve predictions of frost heave and thaw settlement in response to climate change, among other applications.

Although permafrost maps do not exist at relevant scales, good route planning for road construction is critical to avoid problematic interactions with permafrost. Guidelines proposed by TAC (2010) are to:

1. Minimize stream crossings by using high-resolution aerial photography to identify the drainage conditions and patterns, as well as using the best available hydrologic methods to determine design flow parameters.
2. Protect the natural vegetative mat that insulates ice-rich permafrost, and perform clearing and site preparation work along proposed road corridors only in winter when the active layer is frozen and the vegetation mat is covered by snow.
3. Where large-diameter culverts cannot be avoided, use the riveted or bolted type, and consider the installation of polystyrene insulation beneath the culvert on the bottom of the bedding material and sloped sides of the excavation.
4. Utilize interceptor ditches along fills to help prevent thawing of permafrost by intercepting the water, preventing pooling of water along the toe of embankments, and preventing water infiltration under and through embankments. Design them with additional capacity and allow initial slumping and regrowth of natural vegetation.

Reduced visibility from falling or blowing snow can be anticipated with some accuracy, but these estimations rely on good meteorological observations and forecasts. Methods described by Baggaley and Hanesiak (2005) and Huang et al. (2008) have potential for integration into mining and transportation operations to help predict periods of dangerously reduced visibility, as well as for anticipation of when conditions will clear and operations can resume. These methods become more reliable (i.e., resulting in fewer ‘false alarms’) at both higher wind speeds and lower threshold visibilities (e.g., 500 m visibility versus 1 or 2 km). Forecasts require observations including time since last snowfall, ground and surface temperatures, wind speed and wind direction measurements. These are all measures which can be automated using the correct equipment. These authors have also suggested a number of methods to further simplify blowing snow forecasts using ‘nomograms’, which are simply graphs indicating the probability of occurrence of blowing snow given current or future weather conditions.

Smithson (2004) lauded the significant improvements in winter maintenance which have occurred in recent decades, improvements that have been due in particular to anticipatory maintenance actions and better practitioner education. Smithson was mainly referring to a computer-based training program developed by the American Association of State Highway and Transportation Officials (AASHTO) in the early 2000s, which was intended to encourage practitioners to take advantage of available technological advances. The program included modules such as “Weather Basics” and “Weather and Roadway Monitoring”. A number of jurisdictions have reported substantial benefits accruing from this program, with various agencies reporting a 200%-1300% return on investment. A tailored version of this software could be useful for training and outreach (McGregor et al., 2008) in the North, and include additional modules discussing Arctic weather, climate change in the North, and winter roads. A "Winter Severity Index" has been developed to aid with winter road maintenance for southern Canada that is based on the variability of maintenance costs for different regions in the country (Suggett et al., 2006). It may be possible to generate a similar index for assessment of roads in northern Canada if such a software program is desired.

In large portions of the United States and Canada, 'storm spotter' networks of volunteers communicating over ham radios (called SKYWARN and CANWARN, respectively), assist with the monitoring and reporting of severe summer weather. Spotters are trained to identify potentially severe and damaging weather and report their observations to local weather offices. These observations assist in the forecasting and dissemination of weather warnings and advisories. A similar concept could be applicable to those users of winter roads in Canada's North, although equipment capable of transmitting over large distances would be required for this. Reports of localized reduced visibility, drifting, and poor traction from snow, as well as other phenomena affecting road conditions, could be reported and communicated among drivers; these reports could eventually be received and recorded by Environment Canada and the respective departments of transportation.

Detailed monitoring of infrastructure is another potential option for adaptation which would provide much needed new data. Sidawi and Shehata (2008) provided examples of such 'infrastructure health monitoring' (IHM) systems for bridge structures in Manitoba. These are currently monitored by stress and strain sensors embedded within the structure, concurrently with meteorological sensors of ambient conditions. This combination provides in-depth data on the behaviour of bridge structures under varying meteorological conditions and operational loading. These data provide some of the first field observations of internal structural behaviour, and will greatly assist in maintenance decisions and in improving knowledge of in-service loading response and long-term climate impacts on structures.

3.7.8. Adaptation Tools

3.7.8.1. Travel Information Systems (TIS)

The governments of Yukon[12] and NWT[13] both provide weather and road conditions information for their highway systems. NWT provides slightly more detailed information, including weight limits for winter roads. Other jurisdictions have developed their own TIS, which provide a framework for further development options, including Ontario (McClintock and Barbetti, 2006) and New Brunswick (Grant and Morrison, 2006). Grant and Morrison (2006) identified sensitivities, challenges, and needs in New Brunswick for particular road users (e.g., long commutes for school children in remote areas) and routes (e.g., importance of ferries along some routes), and attempted to develop strategies to address these. TIS have also included components of historical data that identity 'trouble spots' which may be the focal point for maintenance or emergencies in the near future.

Challenges and needs for TIS include the following: partnerships, data sharing, interoperability (i.e., must 'fit' with adjacent jurisdictions), liability statements (i.e., information "not intended to relieve travellers of their responsibility") and privacy (Grant and Morrison, 2006). Solutions for TIS in southern parts of Canada including cell phone networks (Alkoka, 2005) and internet coverage (McClintock and Barbetti, 2006) may not be applicable in the North, since

12. http://www.511yukon.ca/

13. http://www.dot.gov.nt.ca/_live/pages/wpPages/roadConditions.aspx

communication networks are limited in most areas. Ian Church (pers. comm., 2013), for instance, indicated that the fibre-optics communications network in Yukon is often the first system to fail during severe weather events. Improved TIS in the North will be a particular challenge, and may need to coincide with improved communication networks in order to be successful.

3.7.8.2. Road user outreach

The need for the provision of educational material for road users is one of the more commonly suggested tools (McGregor et al., 2008). Quebec's Ministry of Transportation (MTQ) has developed a unique public educational tool in the form of the first provincial transportation department website on climate change (Hotte et al., 2005). It is broken down into four thematic areas: a climate change primer, a "Towards Sustainable Mobility" page discussing GHG emissions reductions strategies, a transportation and climate change page focusing on emissions, and a page about adapting transportation to the impacts of climate change. The adaptation and impacts section is further divided into four priority sectors: coastal erosion, decreased water levels in the Saint Lawrence, permafrost thaw in the North, and increased variability in winter weather. In terms of public outreach, similar websites could be developed for the northern territories, and could include the latter two adaptation and impacts categories.

3.7.8.3. Decision support systems

Arsenault (2007) provided an example of the infrastructure needed for an effective maintenance decision support system, such as the one that was recently implemented in Quebec. One innovation was a form of visualisation in which observations were combined with forecast values to help anticipate worsening weather conditions, and therefore help prepare for the necessary maintenance actions. These data have also been used to identify previously undocumented event sequences which lead to hazardous road conditions. However, these systems are very 'data hungry' and therefore implementation in the North is a challenge.

3.8. Gaps and Limitations

A key finding among all sources is the need for increased and improved baseline data for analyses and decision making, the details of which are discussed below. The most recent IPCC assessment results for Polar Regions (Anisimov et al., 2007) indicated similar findings, noting that efforts should focus on determining important 'hot spots' for changing climate and should increase monitoring of climate and natural systems. This was found not only in terms of scientific analysis; the need for raw data input is also significant for use in design and maintenance of both mines and transportation infrastructure.

Another common theme was a lack of compiled data (i.e., centralized data sets). Even in cases where data were available, it existed in a variety of formats or was difficult to access. Prowse et al. (2009) have suggested that "the most relevant information" on climate change adaptation activities remains scattered among consultants, government and news media reports and has yet to be compiled. Haley et al., (2011) discussed existing challenges in comparing mining data between nations, noting, as one example, the amount of data that remains in non-digital format.

3.8.1. Mining

3.8.1.1. Representation of polar mining in research and data

In most cases, the survey-based research that is currently available offers very little representation from northern mines. In the only known survey of Canadian mining practitioners on climate change perceptions, only 1 out of 62 respondents consulted was from a northern mine (Ford et al., 2011; Pearce et al., 2009, ch. 7). The suite of case studies, however, did address mines in northern Canada (Pearce et al., 2011).

Baseline data on the mining industry itself is inconsistent, particularly from an international perspective. It is therefore difficult to detect trends and impacts of various drivers, including both the financial and the climatological (Haley et al., 2011). There is no circumpolar mining dataset to compare the relative influences of the drivers, and temporal coverage is particularly difficult given the amount of information which is still on paper and remains to be digitized (Haley et al., 2011). Another major gap in information is that there is no database of abandoned mines in Canada (Pearce et al., 2011; I. Church, pers. comm., 2013), especially considering the potentially massive costs of clean up and remediation. This is of particular concern for Yukon due to its long history of mining, and where many mines contain hazardous materials and pose a risk to local environments and populations.

3.8.1.2. Knowledge gaps and their effects on mining adaptation measures

Senior management representatives were found to be less likely to believe that climate change poses a risk to mining operations (Ford et al., 2010), which may act as a barrier to the implementation of adaptation strategies. Of the perceptions and attitudes of some members of the industry, the most important as cited by Pearce et al. (2009) was the climate change skepticism revealed in industry journals, and the belief that future change will have no impact on future operations.

This skepticism, when combined with the monetary and time costs associated with adaptation and lack of adaptation knowledge, has likely led to a 'slow response' taken by many companies, even in sectors where impacts appear to already be occurring (Pearce et al., 2009). It is apparent that, in terms of design, practitioners prefer specific values based on return period calculations for climatic or hydrological loading rather than incorporating the percentages and uncertainty associated with climate projections (Pearce et al., 2011; I. Church, pers. comm., 2013). This attitude is potentially dangerous given the possible inability of historical data to provide the needed safety margins for operations (e.g., tailings containment facilities). The multiple requests for untreated water release by the Minto mine in 2008, 2009 and 2010, for instance, may be an indication of inadequate design for current climate and weather conditions. This would inevitably result in a lack of design consideration for future climatic shifts. Use of old or out-of-date design criteria based on past climate data has already been identified as a vulnerability for decommissioned and abandoned mines; however, this problem will continue if practitioners continue to employ the same methods for new construction. Some of these uncertainties can be alleviated with a "thorough and rigorous" evaluation of climate-change impacts on mining infrastructure (Pearce et al., 2009).

There are also indications of a knowledge gap between scientific findings and perceived impacts among mining practitioners. When those interviewed were asked about the effects of specific types of weather events consistent with climate change projections, they were twice as likely to note that they would have a negative impact on mining operations, compared to when they were asked if climate change in and of itself would have a negative impact (Ford et al., 2011). This indicates a need for better outreach to make climate change science more accessible to practitioners, including a discussion of the nature and potential of adaptation measures, and possible beneficial opportunities presented by changing conditions. Pearce et al. (2009) noted a general lack of emphasis on adaptation in the mining industry, particularly in industry literature and management attitudes. They also noted a sense that climate-change impacts will be overwhelmingly negative, all of which could be addressed through better outreach. This knowledge gap is also exemplified by the need for expert practitioners for options that are not yet codified (Pearce et al., 2011).

3.8.2. Ground-based Transportation Sector

3.8.2.1. Prohibitive costs of design measures

Most design solutions to maintain permafrost are prohibitively expensive (Table 5), particularly in consideration of both the vast distances and small population base, and by extension, the small tax base, in Yukon and NWT. It is for these reasons that less-expensive adaptive management and design measures have been incorporated in recent transportation projects (McGregor et al., 2008; Nima et al., 2006).

Table 5. Cost per kilometre of permafrost protection strategies (Reimchen et al., 2009).

Strategy	Cost per km
snowsheds/sunsheds	$156,000
vegetation	$11,000
reflective surface	$51,000
ACE	$125,000 - 190,000
ventilation ducts	$121,000
heat drains	$245,000 - 513,000
dry bridge	N/A (very large)

There are special issues associated with the construction of road infrastructure in remote areas, particularly when budgetary restrictions are a dominant concern (e.g., Great Bear River Bridge; Nima et al., 2006). McGregor et al. (2008) suggested that, in light of the high costs of some adaptation design methods, (e.g., switching from winter to all-season roads), other more gradual design and maintenance measures should be applied as alternative adaptation options for northern roads. They note that "…technology alone could not achieve satisfactory risk reduction, has shifted the objective to an examination of a wider range of adaptation strategies…" (McGregor et al., 2008, p. 10) However, they also noted that "increased vigilance" through improved monitoring, traffic management and outreach (e.g., driver awareness) are also critical components with this approach. Again, the close monitoring of conditions through observations is indicated as a key component of adaptation measures. Prowse et al. (2009) also identified monitoring as an "important element of any adaptation response."

3.8.2.2. Site-specific studies and interdisciplinary barriers

Stephenson et al. (2011) noted that there is a gap in site-specific studies on the financial impact of climate change, which are necessary to properly quantify impacts on costs (e.g., studies of specific port facilities, fueling stations). While their study indicated the potential secondary snow impacts of increased ground-surface and ice-surface insulation, primary snow impacts due to extreme snowfall, flooding and washouts from run-off, or blowing-snow incidents were not factored into travel-time assessments for future scenarios. The 2012 Nahanni Range Road washouts in Yukon, for example (see Table 6, below), rendered the road impassable for over one week (CMJ, 2012a,b). Heavy snowfall may not block roads, but reduced visibility and increased travel difficulty will increase travel times; this could lead to significant shipment delays on busy winter roads, thus decreasing transportation efficiency. Site-specific impact studies may provide an excellent opportunity to incorporate extreme weather events into planning and operations.

Methods used for sector-specific studies of climate-change impacts may also be inconsistent with best practices. Crowder et al. (2008) investigated future potential impacts of climate change on load restrictions for roads in northern Manitoba. For future temperature projections, a single GCM was employed to drive a mesoscale meteorological model. A single year, 2044, was then compared to historical values that had been averaged over a 15-year period. This contrasts with current suggested methodologies, which indicate multi-model ensembles and related approaches (IPCC, 2012). However, Crowder et al. (2008) also compared backcasted GCM results with observed climate normals, which is an important step that is consistent with IPCC recommendations. While results of their study are consistent with other projections of the impacts of climate change, the methodology may raise serious doubts about particular findings. This is not intended as a criticism of Crowder et al. (2008); this highlights the lack of available guidance and dearth of information on climate change impact studies for infrastructure that have been updated to practices consistent with IPCC studies and other climate expertise. This is particularly true regarding the selection and use of climate models, both GCMs and RCMs.

3.8.2.3. Data and information needs for transportation

Milligan and Montufar (2011) discuss the need for performance measures tailored to northern roads, since a number of specific measures used in southern Canada are simply not applicable to, or representative of, conditions in the North. The aforementioned 'winter severity index', which has been developed to aid in assessing winter road maintenance requirements, is a good example (Suggett et al., 2006). The study was successful in finding statistical correlations between road maintenance costs, climate/weather variables (e.g., precipitation, temperature, drifting snow), and the winter severity index; however, a number of issues render it far less effective for application in Yukon and NWT. Road maintenance and meteorological data were only collected and assessed for highways and urban centres in southern Canada; furthermore, this version of the index is primarily based on the use and costs associated with road salt, as this was determined to be the best maintenance variable related to meteorological conditions. Thus, the index is simply not applicable to winter roads, which is particularly significant for NWT since nearly half of the total road length in the territory during the cold season consists of winter roads. Finally, Suggett et al. (2006) noted that the best statistical fits were found in urban centres (i.e., locations with the best observational data), again decreasing its utility in the sparsely populated North. A similar index could conceivably be developed for northern regions based on other, more common maintenance indicators (i.e., those related to winter road maintenance), but its generation would require several years of both road maintenance records and meteorological records.

Gaps may also exist in updating of climate information used in guides, codes and standards. For example, a review of TAC guidance material revealed potential gaps relating to temperature data used in road design. While only applicable to all-season roads, the climate data contained in documents such as *Determining the Winter Design Temperature* (TAC, 1997) and *SHRPBIND weather database: Canadian weather station data* (EBA, 1996), data which are used for pavement design, are likely significantly out of date. Given recent temperature trends, especially in the North, nearly two decades of additional warming would likely change design temperatures significantly, either leading to maintenance problems or wasted materials due to overdesign for milder conditions.

Arsenault (2007) described a number of barriers to developing a decision support system for winter maintenance, including "a flagrant lack of instrumentation," lack of knowledge regarding weather risks, and a lack of confidence in available weather forecasts. Keeping in mind that this was a system implemented in the second most populated province in Canada, it is likely that implementation in NWT and Yukon would be even more challenging based on capacity challenges.

3.8.3. Permafrost and Snow

3.8.3.1. Snow-related maintenance measures

The regular re-assessment of structures for susceptibility to snow load collapse should become a standard component of building and site maintenance, since collapse risk will change over time due to both structural (e.g., modifications, aging) and climate factors (i.e., climate change driven increases in loading; GNWT, 2004a).

3.8.3.2. Lack of quality observational data

Perhaps the most consistent theme throughout the literature was a consistent lack of quality meteorological observational data. This lack of data required the use of stations (as a proxy) that are significant distances from the location of study; it prevented certain types of analysis; and it generated frustration when data were of low quality or certain fields were missing. A few examples are listed as follows:

"Unfortunately, we have not found any descriptions of the snow cover against which we can compare our 2007 measurements." (Derksen et al., 2009)

"Climate and stream flow records from the NWT are sparse and of short duration." (St. Jacques and Sauchyn, 2009)

"[The] quality of winter maintenance program is closely linked to the quality of the data…" (Arsenault, 2007)

"Unfortunately, a consistent record of meteorological observations for the entire period of [study] was not available at either [automatic weather station]." (Howell et al., 2012)

"It was unfortunately not possible to evaluate NOAA SCE across Arctic Canada during the period after 2008 as there are now too few stations reporting snow depth observations." (Derksen and Brown, 2012)

This dearth in observational data coverage in the North, most notably the spatial extent and station density, is particularly significant when considering the diversity of the climate within the study region. Yukon, for example, contains 23 different ecoregions, making it the most spatially diverse jurisdiction in Canada (I. Church, pers. comm., 2013). NWT has 42 such regions, but these are spread over a much larger area. The combination of complex geology and microclimates indicates that spatial density of data needs to be much higher than it is currently in order for measurements to reflect the true spatial variability of northern climate.

3.8.3.3. Snow water equivalent (SWE)

SWE data appeared to be the most troublesome measure of snow, as indicated repeatedly in the literature on snow and spring run-off (Howell et al., 2012; Brown and Mote, 2009, Yang et al., 2009). Its critical importance relating to impacts is combined with the uncertainty and difficulty associated with measuring SWE in remote locations. There is no quality-controlled global dataset with which to assess climate model performance, and it is among one of the most difficult snow characteristics to assess and model (Brown and Mote, 2009). Brown and Mote (2009) for example, were forced to use previously observed seasonal snow density climatology to estimate SWE, which are likely no longer valid due to changes in snow characteristics. The climatology also does not take into account short-term evolution or behaviour of the snowpack, both of which are of critical importance to potential impacts. For example, Langlois et al. (2009) conducted an assessment of three models for SWE estimation in southern Quebec. They had noted the only year where results deviated significantly from model values was the winter of 2007-2008, which was incidentally a year in which several buildings suffered snow load collapses or damage; this resulted in three fatalities as well as school closures and other impacts (Descurieux, 2010). See also Derksen et al. (2009) for more detailed discussion of passive microwave detection SWE algorithms and biases.

The climate change assessment methodology of many of the studies that were collected may be insufficient by current IPCC guidelines or best practices, as discussed above (Crowder et al., 2008).

3.8.3.4. Outreach programs

The apparent knowledge gap exhibited by practitioners and the public in general has led to the suggestion that education and outreach regarding the impacts of climate change and weather hazards needs further emphasis (Pearce et al., 2011). For example, Campbell et al. (2008) specifically recommended the development of an avalanche public safety program for Yukon. The Yukon Avalanche Association (YAA) was developed in 2010 and provides such a service for a small region of the Yukon/BC border, and has achieved significant success in spite of tight budget constraints. Their work includes a small meteorological observation network, an information website, the development of staff, and the execution of outreach activities (Smith and Sharp, 2012). The YAA is currently focused on the needs of backcountry users (e.g., snowmobilers, skiers), and the expansion of such a program to encompass transportation and mining activities (beyond the South Klondike Highway which already has an avalanche control program), would be an excellent next step. Nearly one quarter (24%) of all recorded avalanche deaths in Canada have been from resource extraction activities or along transportation routes (Campbell et al., 2008); this indicates that these are indeed vulnerable activities.

3.8.3.5. Need for forensic studies of high-impact events

In terms of snow impacts, it was noted that there was a dearth of region-specific studies in the published or grey literature. Pearce et al. (2009) also indicated the need for more “case specific research” following their literature review. A number of high impact snow-related events have already occurred in the North, which could be the subject of such forensic studies. These would further our knowledge of the extent and severity of snow-related hazards, as well as help determine snow-related ‘thresholds’ for infrastructure impacts. These could include values at which preventative maintenance or safety action is needed (e.g., “event triggered maintenance”; MAC, 2011d) or failure and breaking thresholds for loads (e.g., snow load roof collapse, tailings containment breach, road washout, etc.). Event sequences (such as rain-on-snow or high-runoff years which lead to impacts) and so called “complex extremes” (Benestad and Haugen, 2007; Stephenson, 2008), are also important since they are the result of more than one discrete weather event.

The listings in Table 6, below, provide some examples of these types of impacts noted in the territories, indicating those events which could benefit from further investigation. A database of high-impact events could also be developed to further aid in forensic analysis; this would also allow for the inter-comparison or ranking of individual events to prioritize research needs.

Table 6. Example of snow hazard-related events.

Event (Date)	Notes (Reference):
snow load roof collapse; Enterprise, NWT (January 28, 2013)	small municipal garage collapsed under heavy snow, damaging vehicles inside; contractors hired to remove snow from roofs of other municipal buildings (Bickford, 2013)
flooding, rain-on-snow; SE Yukon (June 2012)	Nahanni Range Road wash outs, cutting off access to CanTung Mine; resumed operation in just over one week (CMJ, 2012a,b); Lower Post, BC (8 km south of YT border) evacuated, estimated $3-4 million in damage (CBC, 2012a)
flooding, snow melt; Qikiqtarjuaq, NU (June 5 and 6, 2012)	airport runway flooded on June 5th; second flood on June 6th washed out access road to sewage pond and dump (CBC, 2012b)
blowing snow/blizzard; NWT (March 20-21, 2012)	four vehicles stranded overnight on Wekweeti winter road due to whiteout conditions; RCMP search delayed overnight due to weather conditions (CBC, 2012c)
flooding, rain-on-snow; Pangnirtung, NU (June 8 to 9, 2009)	high water from combined rainfall and snowmelt eroded permafrost at bridge abutments, damaging two bridges and bridge access roads; town received disaster financial assistance from federal government (Water Canada, 2009)
excessive spring meltwater; YT (June and July 2009)	Minto mine requested release of 300 million litres of untreated water into local waterways due to excessive spring runoff (Thompson, 2009; Munson, 2009b).*
snow-load roof collapse; Yellowknife, NWT (April 2009).**	Partial collapse of 4.5 x 9 m section of warehouse at local home improvement store (Robinson, 2009)
rain-on-snow event; Daring Lake, NWT (April 7, 2007)	no impacts due to remote nature of location, however very early in season for such an event; detected due to IPY-related research (Derksen et al., 2009)
snow load roof collapse; Inuvik, NWT (May 2004)	roof of Samuel Hearn Secondary School collapsed under snow loading, triggering an evaluation of 151 government buildings across NWT; 14 additional structures were identified high risk (GNWT, 2004a)
spring flooding; Mayo, YT (spring 1936)	most severe flood on record crested at 4.8 m above high-water mark, due to combination of heavy snowfall and a late, but warmer than usual spring (NCE, 2011b)

*Also a washout along a 4 km portion of mine haul road by torrential rains in August 2008 (as cited in Pearce et al., 2011).

**Snow-load roof collapse of local ice rink also occurred at Fond-du-Lac, SK, ~78 km south of NWT border, March 29th, 2009 (CP, 2009).

4. CONCLUSIONS

Based on the literature review, a series of conclusions and recommendations were generated in the form of observations and suggestions for future work.

4.1. Transportation

Many adaptation design measures are quite costly. For the transportation sector in particular, this is a concern which is compounded by the vast distances which need to be covered in Yukon and NWT combined with a small population base that is available for financial support of infrastructure. In many cases, alternative adaptation methods, particularly management practices and low-cost design alternatives, have been implemented. More complex links between climate change and precipitation, particularly snow-rain interactions, may play a significant role in ice road behaviour (Rawlings et al., 2009).

More difficult surface travel in the territories will have specific consequences for transportation costs and efficiency; however, research also indicates that improved management practices may be capable of absorbing and mitigating some of these impacts (Rawlings et al., 2009). Increases in resupply costs to remote communities could be mitigated by switching to air travel for a defined, limited time period (Stephenson et al., 2011). With increased difficulties in maintaining surface travel, there will be a smaller window for the mining, energy and timber industries to transport product and equipment (Stephenson et al., 2011). Shorter operating seasons for some winter roads increases vulnerability to delays and closures. Studies did not address other factors which will affect transportation efficiency, for example, heavy snowfall and blowing snow events, as well as potential benefits from changes in management practices and road design (McGregor et al., 2008).

4.2. Mining

Although only tangentially addressed in the literature, the issue of abandoned and decommissioned mines is extremely costly and should be investigated more thoroughly. There was a noted gap in case studies on abandoned or decommissioned mine sites and the future impacts of climate on these sites. There are countless opportunities for such a study and the lack of even a national database or catalogue of these sites strongly indicates the need to address this issue.

4.3. Knowledge Gaps

There are important knowledge gaps among the different fields of study, which need to be addressed through interdisciplinary cooperation and outreach or guidance material. Several studies indicated a lack of concrete knowledge among practitioners and other representatives of the mining and transportation industries, including end-users of transportation infrastructure, regarding the potential impacts of climate change; this indicates the need for tailored outreach products (e.g., informational websites; Arsenault, 2007).

Several studies employed only a single climate model for climate change projections, whereas current IPCC best practice suggests a multi-model ensemble approach. Best practice also suggests that studies should include testing for best model selection, in particular for events dependent on more localized, smaller-scale or physically complex conditions (IPCC, 2012).

There are clearly important regional differences in snow and temperature behaviour which indicate the need for further research (e.g., apparent decreases in snow pack in parts of southern Yukon; Janowicz, 2010). Variability in future climate trends between regions indicates the need for different adaptation strategies.

4.4. Future Work

Research also highlighted a number of items which merit further research and analysis, including a number of potential deliverable items which could be addressed in the next phase of this project.

4.4.1. Data Sharing

Data sharing between agencies should become a priority, including an effort to generate the highest quality and most easily accessible joint meteorological and permafrost databases. Participation and cooperation between private, government, and academic agencies could lead to a highly beneficial, centralized dataset for the use and benefit of all participants, given the clear demonstration of common climate data needs (e.g., accessibility to borehole data could result in an excellent permafrost monitoring network).

4.4.2. Best Practices

An interdisciplinary team of experts should be called upon to develop best practices guides for the following:

- construction techniques on various types of permafrost;
- use of climate-change modelling for infrastructure design and impacts assessments;
- outreach material providing targeted plain language climate-change information relevant to specific sectors, for informing clients, stakeholders and end-users; and
- selection and identification of extreme weather events for hazard assessments of specific mine sites.

4.4.3. Mining

Stratos Inc. (2009) define a range of reactions from the mining industry, from proactive measures, to awareness with no action, to actively ignoring business and environmental risks associated with climate change. A move toward proactive management should be encouraged in the mining industry (MEND, 2009a,b). Outreach material targeted at the mining industry would assist in promoting proactive management of climate-change impacts.

Further investigation is required on the potential impacts of climate change on mining drainage. Research should be conducted on this topic, particularly for abandoned and post-closure mines. An analysis should be conducted on the potential impact of changes in precipitation regimes on mining drainage. This study should investigate the magnitude of impacts to determine the significance of climate-change impacts on future drainage characteristics and to inform possible adaptations.

4.4.4. Permafrost

Some of the most important measures in terms of impacts to mining and transportation are among the most difficult to measure and assess, in particular active layer depths for permafrost and snow water equivalent values. Further refinement of permafrost models is needed.

4.4.5. Research Suggestions

More localised climate change impacts studies, such as those conducted by NCE for locations in Yukon, should be executed. These highlight the regional or location-specific differences in climate and climate change trends. They also provide both site-specific and actionable information and recommendations.

A more thorough analysis of precipitation trends in Yukon and NWT is necessary to update previous work (Stone et al., 2000), generate regional studies similar to those carried out in other Arctic regions (Ye et al., 2009), and to better quantify apparent regional differences (e.g., increases in snow fall in northern Yukon versus decreases in the south; Janowicz, 2010).

The assumption has been made in numerous studies that all winter flow in many rivers (e.g., January to end of March; St. Jacques and Sauchyn, 2009) is due solely to sub-surface/ groundwater flow through the active layer. However, a number of winter snow melt and rainfall events have occurred in recent years, and their contribution to changes in hydrology should be further investigated.

4.5. Planned Research

Several ongoing projects promise to provide supportive research for these issues, and new findings should be communicated to the mining and transportation industries. An example is GNWT's current project updating the previous snow load roof collapse risk assessment methodology (GNWT, 2004a-c). This is being completed in collaboration with AE Engineering and Risk Sciences International. They are expanding the method to include all climatic loads and permafrost impacts to better assess individual building risk for current and future climate.

4.6. Next Steps

The next phase of the project involves interviews with practitioners from both the transportation and mining sectors. Analysis of the interview results will include the current knowledge and practices within the two sectors, as well as identify knowledge gaps and potential knowledge products. The information from the literature review and the practitioner interviews will be used to generate a list of potential knowledge products that will be disseminated for feedback to project advisors. The Project Team will identify knowledge products that address issues established in the literature review and practitioner interviews, and respond to the needs of the sectors that are possible within the scope of the project. One or two of these products will be selected as deliverables, and draft products will be produced and shared with the Project Advisory Committee for feedback.

5. REFERENCES

Aboriginal Affairs and Northern Development Canada (AANDC), 2013. Snow Surveys. Accessed December 21, 2013, http://www.aadnc-aandc.gc.ca/eng/1100100027479/1100100027483.

ACIA, 2005. Arctic Climate Impact Assessment. Cambridge University Press, 1042 p.

ADOTPF (Alaska Department of Transportation and Public Facilities), 1985. White paint for highway thaw settlement control. Alaska Department of Transportation and Public Facilities, Juneau, AK, p. 1-35.

Alkoka, M.M., 2005. Beyond road weather information as a decision-making tool in winter maintenance operations, what else is needed? Transportation Association of Canada, Calgary, AB, p. 1-6.

Anisimov, O.A., Vaughan, D.G., Callaghan, T.V., Furgal, C., Marchant, H., Prowse, T.D., Vilhjálmsson, H. and Walsh, J.E., 2007. Polar Regions (Arctic and Antarctic). Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, eds., Cambridge University Press, Cambridge, p. 653-685. http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch15.html.

Arsenault, S., 2007. Development of a winter maintenance decision support system. Transportation Association of Canada, Saskatoon, SK, p. 1-16.

Baggaley, D.G. and Hanesiak, J.M., 2005. An empirical blowing snow forecast technique for the Canadian Arctic and the prairie provinces. Weather and Forecasting, vol. 20, p. 51-62.

Beaulac, I. and Doré, G., 2006. Airfields and access roads performance assessment in Nunavik, Quebec, Canada. Current Practices in Cold Regions Engineering 2006, p. 1-11, doi:10.1061/40836(210)61.

Benestad, R.E. and Haugen, J.E., 2007. On complex extremes: Flood hazards and combined high spring-time precipitation and temperature in Norway. Climatic Change, vol. 85, p. 381-406.

Benn, D.I. and Evans, D.J., 2010. Glaciers and Glaciation. Hodder Education, London, UK, 816 p.

Bickford, P., 2013. Heavy snow load has hamlet concerned. Northern News Service Online, http://www.nnsl.com/frames/newspapers/2013-02/feb11_13sno.html.

Bjelkevik, A., 2005. Water cover closure design for tailings dams. http://epubl.ltu.se/1402-1528/2005/19/LTU-FR-0519-SE.pdf.

Bond, J.D. and Lipovsky, P.S., 2011. Surficial geology, soils and permafrost of the northern Dawson Range. Yukon Exploration and Geology 2010, K.E. MacFarlane, L.H. Weston and C. Relf (eds.), Yukon Geological Survey, p. 19-32.

Bonnaventure, P.P., 2006. Validation of the Basal Temperature of Snow (BTS) method to map permafrost in complex mountainous terrain, Ruby Range, YT and Haines Summit, BC MSc thesis, Department of Geography, University of Ottawa, Ottawa, ON, 121 p.

Brabets, T.P. and Walvoord, M.A., 2009. Trends in streamflow in the Yukon River Basin from 1944 to 2005 and the influence of the Pacific Decadal Oscillation. Journal of Hydrology, vol. 371, p. 108-119.

Braden, B., 2012. Friggin' freezin': Renowned winter road readies for really big traffic. Canadian Mining Journal, vol. 133, p. 24-25.

Brown, J., Ferrians, O.J., Heginbottom, J.A. and Melnikov, E.S., 1997. International Permafrost Association Circum-Arctic Map of Permafrost and Ground Ice Conditions. U.S. Geological Survey Circum-Pacific Map Series, Map CP-45, scale 1:10,000,000.

Brown, R.D. and Mote, P.W., 2009. The response of northern hemisphere snow cover to a changing climate. Journal of Climate, vol. 22, p. 2124-2145.

Burn, C.R., 2007. Permafrost. *In:* Encyclopedia of Quaternary Science, S.A. Elias (ed.), Elsevier, Oxford, UK, p. 2191-2199.

CAC (Canadian Avalanche Centre), 2013. Incident report database. Canadian Avalanche Centre, http://www.avalanche.ca/cac/library/incident-report-database/view.

Campbell, C., Bakermans, L., Jamieson, B. and Stethem, C., 2008. Avalanche threats and mitigation measures in Canada. Whistler, BC, International Snow Science Workshop, p. 836-844.

CMJ (Canadian Mining Journal), 2006. The cost of less cold. Canadian Mining Journal, p. 127

CMJ (Canadian Mining Journal), 2012a. Tungsten Mining: Road Washouts Threaten CanTung Mine. Canadian Mining Journal, Daily News, http://www.canadianminingjournal.com/news/tungsten-mining-road-washouts-threaten-cantung-mine/1001455337/.

CMJ (Canadian Mining Journal), 2012b. Tungsten Mining: CanTung Mine Back in Production. Canadian Mining Journal, Daily News, http://www.canadianminingjournal.com/news/tungsten-mining-cantung-mine-back-in-production/1001495815/.

CBC News, 2009. Section of rink roof collapses in Fond-du-lac, Sask. CBC News, http://www.cbc.ca/news/canada/saskatchewan/section-of-rink-roof-collapses-in-fond-du-lac-sask-1.824029.

CBC News, 2012a. CanTung mine rations fuel due to road closure. CBC News, http://www.cbc.ca/news/canada/north/story/2012/06/14/north-tungsten-road-out.html.

CBC News, 2012b. Qikiqtarjuaq closes part of runway due to flooding. CBC News, http://www.cbc.ca/news/canada/north/story/2012/06/07/north-qikiqtarjuaq-runway-flood.html.

CBC News, 2012c. Snowstorm strands vehicles on N.W.T. ice road. CBC News, http://www.cbc.ca/news/canada/north/story/2012/03/22/north-ice-road-whiteout.html.

Coulombe, S., Fortier D. and Stephani, E., 2012. Using air convection ducts to control permafrost degradation under road infrastructure: Beaver Creek experimental site, Yukon, Canada. Cold Regions Engineering, p. 21-31, http://dx.doi.org/10.1061/9780784412473.003.

Crowder, J., Shalaby, A., Van Cauwenberghe, R. and Clayton, A., 2008. Assessing spring load restrictions using climate change and mechanistic-empirical distress models. Transportation Association of Canada, Toronto, ON, p. 1-11.

Derksen, C. and Brown, R.D., 2012. Spring snow cover extent reductions in the 2008-2012 period exceeding climate model projections. Geophysical Research Letters, vol. 39, p. 1-6.

Derksen, C., Silis, A., Sturm, M., Holmgren, J., Liston, G.E., Huntington, H. and Solie, D., 2009. Northwest Territories and Nunavut snow characteristics from a subarctic traverse: Implications for passive microwave remote sensing. Journal of Hydrometeorology, vol. 10, p. 448-463.

Derksen, C., Smith, S.L., Sharp, M., Brown, L., Howell, S., Copland, L., … and Walker, A., 2012. Variability and change in the Canadian cryosphere. Climatic Change, vol. 115, p. 59-88, doi:10.1007/s10584-012-0470-0.

Descurieux, J., 2010. Post hoc evaluation of hazardous weather: Snowstorms in the Montreal, Quebec, area in March 2008. Weather, Climate and Society, vol. 2, p. 36-43.

Dyer, J.L. and Mote, T.L., 2006. Spatial variability and trends in observed snow depth over North America. Geophysical Research Letters, vol. 33, L16503.

EBA Engineering Consultants Ltd.(EBA), 1996. SHRPBIND weather database: Canadian weather station data (WEATHER). Transportation Association of Canada, 54 p.

EBA Engineering Consultants Ltd. (EBA), 2004. Permafrost Considerations for Effective Mine Site Development in the Yukon Territory. Prepared for Mining Environment Research Group (MERG), MERG Report 2004-1, Government of Yukon, 33 p.

Ford, J., Pearce, T., Prno, J., Duerden, F., Berrang-Ford, L., Beaumier M. and Smith, T., 2010. Perceptions of climate change risks in primary resource use industries: A survey of the Canadian mining sector. Regional Environmental Change, vol. 10, p. 65-81.

French, H.M., 2007. The Periglacial Environment, Third Edition. John Wiley & Sons Ltd., England, 458 p.

Galloway, J.M., Sanei, H., Patterson, R.T., Mosstajiri, T., Hadlari, T. and Falck, H., 2012. Total arsenic concentrations of lake sediments near the City of Yellowknife, Northwest Territories. Geological Survey of Canada Open File 7037, 47 p., doi:10.4095/xxxxxxx.

Ghoreishi-Madiseh, S.A., Hassani, F., Mohammadian, A. and Abbasy, F., 2011. Numerical modeling of thawing in frozen rocks of underground mines caused by backfilling. International Journal of Rock Mechanics and Mining Sciences, vol. 48, issue 7, p. 1068-1076.

Goering, D.J., 1998. Experimental investigation of air convection embankments for permafrost-resistant roadway design. PERMAFROST Seventh International Conference, Yellowknife, YT, Collection Nordicana no. 55, 1998.

Goering, D.J., 2003. Passively cooled railway embankments for use in permafrost areas. Journal of Cold Regions Engineering, vol. 17, issue 3, p. 119-133, doi:10.1061/(ASCE)0887-381X(2003)17:3(119).

Goering, D.J. and Kumar, P., 1996. Winter-time convection in open-graded embankments. Cold Regions Science and Technology, vol. 24, p. 57-74.

GNWT (Government of the Northwest Territories), 2004a. Risk assessment and analysis report: Building roof snow overload. Government of the Northwest Territories, Public Works and Services, 9 p.

GNWT (Government of the Northwest Territories), 2004b. Roof snow overload risk estimation. Government of the Northwest Territories, Public Works and Services, 4 p.

GNWT (Government of the Northwest Territories), 2004c. Roof inspection checklist. Government of the Northwest Territories, Public Works and Services, 4 p.

Government of Nunavut, 2012. Engineering challenges for tailings management facilities and associated infrastructure with regards to climate change in Nunavut. Report no. L-11-1472, 110 p.

Grant, R. and Morrison, J., 2006. Traveller information issues and opportunities for rural areas. Session of the 2006 Annual Conference of the Transportation Association of Canada, Charlottetown, PEI, p. 1-12.

Gruber, S. and Haeberli, W., 2007. Permafrost in steep bedrock slopes and its temperature-related destabilization following climate change. Journal of Geophysical Research, vol. 112, issue F2, doi:10.1029/2006JF000547.

Haley, S., Klick, M., Szymoniak, N. and Crow, A., 2011. Observing trends and assessing data for Arctic mining. Polar Geography, vol. 34, p. 37-61.

Harris, C., Arenson, L.U., Christiansen, H.H., Etzelmüller, B., Frauenfelder, R., Gruber, S., Haeberli, W., Hauck, C., Hölzle, M., Humlum, O., Isaksen, K., Kääb, A., Kern-Lütschg, A., Lehning, M., Matsuoka, N., Murton, J.B., Nötzli, J., Phillips, M., Ross, N., Seppälä, M., Springman, S.M. and Vonder Mühll, D., 2009. Permafrost and climate in Europe: Monitoring and modeling thermal, geomorphological and geotechnical responses. Earth-Science Reviews, vol. 92, issues 3-4, p. 117-171, doi:10.1016/jearscirev.2008.12.002.

Heginbottom, J., Brown, J., Humlum, O., and Svensson, H., 2012. Permafrost and periglacial environments. *In*: State of the Earth's Cryosphere at the Beginning of the 21st Century, R.S. Jr. Williams and J.G. Ferrigno (eds.), USGS Professional Paper 1386-A-5, p. 425-496.

Hennessey, R., Jones, S., Swales, S. and Duerden, F., 2011. Dawson Climate Change Adaptation Plan, Revised Edition. Northern Climate ExChange, Yukon Research Centre, Yukon College, Whitehorse, YT, 64 p.

Hennessey, R., Stuart, S. and Duerden, F., 2012. Mayo Region Climate Change Adaptation Plan. Northern Climate ExChange, Yukon Research Centre, Yukon College, Whitehorse, YT, 103 p.

Holubec, I., 2008. Flat loop thermosyphon foundations in warm permafrost. Prepared for the Government of the Northwest Territories Asset Management Division of Public Works and Services and the Climate Change Vulnerability Assessment of the Canadian Council of Professional Engineers, 119 p.

Hotte, M., Rouleau, K., Ayotte, M. and Villemure, D., 2005. The Ministry of Transportation of Quebec's website on climate change. Transportation Association of Canada, Ottawa, ON, p. 1-9.

Howell, S.E.L., Assini, J., Young, K.L., Abnizova, A. and Derksen, C., 2012. Snowmelt variability in Polar Bear Pass, Nunavut, Canada, from QuikSCAT: 2000-2009. Hydrological Processes, vol. 26, p. 3477-3488.

Huang, Q., Hensiak, J., Savelyev, S., Papakyriakou, T. and Taylor, P.A., 2008. Visibility during blowing snow events over Arctic sea ice. Weather and Forecasting, vol. 23, p. 741-751.

INAC (Indian and Northern Affairs Canada), 2007. Frozen block method: Giant Mine Remediation Project. Aboriginal Affairs and Northern Development Canada, Yellowknife, NWT, 2 p.

IPCC (Intergovernmental Panel on Climate Change), 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and A. Reisinger (eds.)]. IPCC, Geneva, Switzerland, 104 p., http://www.ipcc.ch/ipccreports/assessments-reports.htm.

IPCC, 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. C.B. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor and P.M. Midgley (eds.), Cambridge University Press, Cambridge, UK, 582 p.

Janowicz, J.R., 2010. Observed trends in the river ice regimes of northwest Canada. Hydrology Research, vol. 41, p. 462-470.

Jin, Q., Qi-hao, Y., Yan-hui, Y., Jun, H. and Lei, G., 2013. Analysis on cooling effect of new hollow concrete brick revetment under gravel pavement in permafrost regions. Cold Regions Science and Technology, vol. 85, p. 15-21, doi: 10.1016/j.coldregions.2012.06.003.

Joe-Strack, J. and Janowicz, J.R., 2009a. Yukon Snow Survey Bulletin and Water Supply Forecast: March 1, 2009. Water Resources Branch, Department of Environment, Government of Yukon, 26 p. http://www.env.gov.yk.ca/air-water-waste/snow_survey.php

Joe-Strack, J. and Janowicz, J.R., 2009b. Yukon Snow Survey Bulletin and Water Supply Forecast: April 1, 2009. Water Resources Branch, Department of Environment, Government of Yukon, 26 p. http://www.env.gov.yk.ca/air-water-waste/snow_survey.php

Joe-Strack, J. and Janowicz, J.R., 2009c. Yukon Snow Survey Bulletin and Water Supply Forecast: May 1 2009. Water Resources Branch, Department of Environment, Government of Yukon, 26 p. http://www.env.gov.yk.ca/air-water-waste/snow_survey.php

Jørgensen, A.S. and Andreasen, F., 2007. Mapping of permafrost surface using ground-penetrating radar at Kangerlussuaq Airport, western Greenland. Cold Regions Science and Technology, vol 48, no. 1, p. 64-72.

Keevil, G., 2008. Water, water everywhere, and fewer drops to drink. Yukon News. http://yukon-news.com/news/water-water-everywhere-and-fewer-drops-to-drink.

Kunkel, K.E., Andsager, K. and Easterling, D.R., 1999. Long-term trends in extreme precipitation events over the conterminous United States and Canada. Journal of Climate, vol. 12, p. 2515-2527.

Kunkel, K., 2003. North American trends in extreme precipitation. Natural Hazards, vol. 29, p. 291-305.

Kuyucak, N., 1999. Acid mine drainage prevention and control options. International Mine Water Association Congress, Sevilla, Spain, 1999.

Kyhn, C. and Elberling, B., 2001. Frozen cover actions limiting AMD from mine waste deposited on land in Arctic Canada. Cold Regions Science and Technology, vol. 32, p. 133-142.

Langlois, A., Kohn, J., Royer, A., Cliche, P., Brucker, L., Picard, G. … and Willemet, J.M., 2009. Simulation of snow water equivalent (SWE) using thermodynamic snow models in Quebec, Canada. Journal of Hydrometeorology, vol. 10, p. 1447-1463.

Lemke, P., Ren, J., Alley, R.B., Allison, I., Carrasco, J., Flato, G., Fujii, Y., Kaser, G., Mote, P., Thomas, R.H. and Zhang, T., 2007. Observations: Changes in snow, ice and frozen ground. *In:* Climate Change 2007: The Physical Science Basis (Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change), S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.), Cambridge University Press, Cambridge, UK and New York, NY, p. 337-383.

Lepage, J.M.J. and Doré, G., 2010. Experimentation of mitigation techniques to reduce the effects of permafrost degradation on transportation infrastructures at Beaver Creek experimental road site (Alaska Highway, Yukon). *In:* Proceedings from the 63rd Canadian Geotechnical Conference (GEO2010), C. Kwok (ed.), Calgary, AB, p. 526–533, http://136.159.35.81/cpc/CPC6-526.pdf [accessed February 18, 2013].

Lepage, J.M.J., Doré, G. and Fortier, D., 2012. Thermal effectiveness of the mitigation techniques tested at Beaver Creek experimental road site based on a heat balance analysis: Yukon, Canada. Cold Regions Engineering 2012, p. 42-51, doi:10.1061/9780784412473.005.

MAC (Mining Association of Canada), 2011a. TSM assessment protocol - a tool for assessing tailings management performance, 24 p.

MAC (Mining Association of Canada), 2011b. TSM assessment protocol - a tool for assessing energy use and greenhouse gas emissions management performance, 25 p.

MAC (Mining Association of Canada), 2011c. A guide to management of tailings facilities (2nd edition), 68 p.

MAC (Mining Association of Canada), 2011d. Developing an operation, maintenance and surveillance manual for tailings and water management facilities, 52 p.

MAC (Mining Association of Canada), 2011e. A guide to audit and assessment of tailings facility management, 60 p.

McClintock, H. and Barbetti, L., 2006. Road condition weather information systems automatically feeds travelers' road information portal at the Ministry of Transportation, Ontario. 2006 Annual Conference, Transportation Association of Canada, Charlottetown, PEI, p. 1-10.

McGregor, R.V., Hassan, M. and Hayley, D., 2008. Climate change impacts and adaptation: Case studies of roads in Northern Canada. 2008 Annual Conference of the Transportation Association of Canada, Toronto, ON, p. 1-15.

Mekis, É. and Brown, R.D., 2010. Derivation of an adjustment factor map for the estimation of the water equivalent of snowfall from ruler measurements in Canada. Atmosphere-Ocean, vol. 48, issue 4, p. 284-293.

MEND (Mine Environment Neutral Drainage Program), 2004. MEND Report 1.61.4: Covers for reactive tailings located in permafrost regions review. Report prepared by I. Holubec Consulting Inc. for Mining Association of Canada and MEND, 134 p.

MEND (Mine Environment Neutral Drainage Program), 2009a. MEND Report 1.61.5a: Mine waste covers in cold regions. Prepared by SRK Consulting (M. Rykaart and D. Hockley, authors) for MEND, 119 p.

MEND (Mine Environment Neutral Drainage Program), 2009b. MEND Report 1.20.1: Prediction manual for drainage chemistry from sulphidic geologic materials. Prepared by W.A. Price of CANMET – Mining and Mineral Sciences Laboratories for MEND, 579 p.

MEND (Mine Environment Neutral Drainage Program), 2011. MEND Report 1.61.7: Climate change and acid rock drainage – risks for the Canadian mining sector. Prepared by Stratos Inc. with contributions from Brodie Consulting Ltd. for MEND, 56 p.

MEND (Mine Environment Neutral Drainage Program), 2012. MEND Report 1.61.5c: Cold regions cover system design technical guidance document. Prepared by O'Kane Consultants Ltd. for MEND, 177 p.

Mesher, D.E., Proskin, S.A. and Madsen, E., 2008. Ice road assessment, modeling and management. 2008 Annual Conference of the Transportation Association of Canada, Toronto, ON, 1-20.

Milligan, C. and Montufar, J., 2011. Performance measurements for roads in the North: Available tools and knowledge gaps. 2011 Conference and Exhibition of the Transportation Association of Canada - Transportation Successes: Let's Build on Them, Edmonton, AB, p. 1-20.

Munson, J., 2009a. Liard River will flood in June: Hydrologist. Yukon News. http://www.yukon-news.com/news/liard-river-will-flood-in-june-hydrologist.

Munson, J., 2009b. Minto wasn't ready for deluge. Yukon News. http://yukon-news.com/news/minto-wasnt-ready-for-deluge/.

NRC (National Research Council), 2010. National Building Code of Canada 2010. National Research Council, Ottawa, ON, 1245 p.

Nelson, F.E., Anisimov, O.A. and Shiklomanov, N.I., 2002. Climate change and hazard zonation in the circum-Arctic permafrost regions. Natural Hazards, vol. 26, p. 203-225.

Nima, M., Lanteigne, M., Wu, Z., Ahmad, N. and Bevington, N., 2006. Challenges of the Great Bear River Bridge. 2006 Annual Conference of the Transportation Association of Canada, Charlottetown, PEI, p. 1-22.

NCE (Northern Climate ExChange), 2011a. Pelly Crossing Landscape Hazards: Geological Mapping for Climate Change Adaptation Planning. Yukon Research Centre, Yukon College, 48 p. and 2 maps.

NCE (Northern Climate ExChange), 2011b. Mayo Landscape Hazards: Geological Mapping for Climate Change Adaptation Planning. Yukon Research Centre, Yukon College, 64 p. and 2 maps.

Osterkamp, T.E., 2003. A thermal history of permafrost in Alaska. Proceedings of Eighth International Conference on Permafrost, Zurich, p. 863-868.

Pearce, T., Ford, J.D., Prno, J., Duerden, F., Berrang-Ford, L.,Smith, T. … and Marshall, D., 2009. Climate change and Canadian mining: Opportunities for Adaptation. Prepared by ArcticNorth Consulting for the David Suzuki Foundation, 160 p.

Pearce, T., Ford, J., Prno, J., Duerden, F., Pittman, J., Beaumier, M., Berrang-Ford, L. and Smith, B., 2011. Climate change and mining in Canada. Mitigation and Adaptation Strategies for Global Change, vol. 16, p. 347-368.

Phillips, D., 1990. The Climates of Canada. Government of Canada, Environment Canada, 176 p.

Prowse, T., Furgal, C., Chouinard, R., Melling, H., Milburn, D. and Smith, S.L., 2009. Implications of climate change for economic development in northern Canada: Energy, resource, and transportation sectors. Ambio, vol. 38, p. 272-281.

Rasmussen, R.M., Vivekanandan, J., Cole, J., Myers, B. and Masters, C., 1999. The estimation of snowfall rate using visibility. Journal of Applied Meteorology and Climatology, vol. 38, p. 1542-1563.

Rawlings, M., Bianchi, R. and Douglas, R.A., 2009. Winter roads and ice bridges: Anomalies in their records of seasonal usage and what we can learn from them. 2009 Annual Conference of the Transportation Association of Canada, Vancouver, BC, p. 1-15.

Räisänen, J., 2008. Warmer climate: Less or more snow? Climate Dynamics, vol. 30, p. 307-12.

Regehr, J.D., Milligan, C.A., Montufar, J. and Alfaro, M., 2012. Review of effectiveness and costs of strategies to improve roadbed stability in permafrost regions. Journal of Cold Regions Engineering, doi:10.1061/(ASCE)CR.1943-5495.0000054.

Reimchen, D., Doré, G., Fortier, D., Stanley, B. and Walsh, R., 2009. Cost and constructability of permafrost test sections along the Alaska Highway, Yukon. Soil Stabilization for Changing Environments Session, 2009 Annual Conference Transportation Association of Canada, 20 p.

Riseborough, D., Shiklomanov, N., Etzelmuller, B., Gruber, S., Marchenko, S. and Etzelmüller, B., 2008. Recent advances in permafrost modelling. Permafrost and Periglacial Processes, vol. 156, p. 137-156, doi:10.1002/ppp.615.

Robinson, A., 2009. Roof collapse shocks owner. Northern News Service Online, http://www.nnsl.com/frames/newspapers/2009-04/apr10_09rf.html.

Romanovsky, V.E., Smith, S.L. and Christiansen, H.H., 2010. Permafrost Thermal State in the Polar Northern Hemisphere during the International Polar Year 2007-2009: A synthesis. Permafrost and Periglacial Processes, Special Issue: The International Polar Year, vol. 21, issue 2, p. 106-116.

Schuur, E.A., Bockheim, J., Canadell, J.G., Euskirchen, E., Field, C.B., Goryachkin, S.V., Hagemann, S., Kuhry, P., Lafleur, P.M., Lee, H., Mazhitova, G., Nelson, F.E., Rinke, A., Romanovsky, V.E., Shiklomanov, N., Tarnocai, C., Venevky, S., Vogel, J.G. and Zimov, S.A., 2008. Vulnerability of permafrost carbon to climate change: Implications for the global carbon cycle. BioScience, vol. 58, issue 8, p. 701-714, http://bioscience.oxfordjournals.org/content/58/8/701.full [accessed February 16, 2013], doi: 10.1641/B580807.

Sidawi, S. and Shehata, E., 2008. Using infrastructure health monitoring (IHM) to assess the impact of climate change on civil infrastructure. Impact of Climate Change on Infrastructure Construction, Maintenance and Operations of the Annual Conference of the Transportation Association of Canada, Toronto, ON, p. 1-12.

Smith, M. and Sharp, E., 2012. Yukon Avalanche Association - the first year and the future. International Snow Science Workshop, Anchorage, AK, p. 214-219, http://arc.lib.montana.edu/snow-science/objects/issw-2012-214-219.pdf.

Smith, M.W. and D.W. Riseborough, 2002. Climate and the limits of permafrost: A zonal analysis. Permafrost and Periglacial Processes, vol. 13, no. 1, p.1-15.

Smithson, L.D., 2004. Performance based winter maintenance operations decision making. 2004 Annual Conference of the Transportation Association of Canada, Quebec City, QC, p. 1-11.

St. Jacques, J. and Sauchyn, D.J., 2009. Increasing winter baseflow and mean annual streamflow from possible permafrost thawing in the Northwest Territories, Canada. Geophysical Research Letters, vol. 36, L01401.

Stephenson, D.B., 2008. Definition, diagnosis, and origin of extreme weather and climate events. Climate Extremes and Society, H.F. Diaz and R.J. Murnane (eds.), Cambridge University Press, Cambridge, UK, p. 11-23.

Stephenson, S.R., Smith, L.C. and Agnew, J.A., 2011. Divergent long-term trajectories of human access to the arctic. Nature Climate Change, vol. 1, p. 156-160.

Stone, D.A., Weaver, A.J. and Zweirs, F.W., 2000. Trends in Canadian precipitation intensity. Atmosphere-Ocean, vol. 38, p. 321-347.

Stratos Inc., 2009. Climate change impacts on mining operations and infrastructure. Report submitted to the Centre of Excellence in Mining Innovation, 15 p.

Suggett, J., Hadayeghi, A., Mills, B., Andrey, J. and Leach, G., 2006. Development of winter severity indicator models for Canadian winter road maintenance. Presentation at the Success in Road Salt Management Session, 2006 Annual Conference of the Transportation Association of Canada, Charlottetown, PEI, p. 1-20, http://conf.tac-atc.ca/english/resourcecentre/readingroom/conference/conf2006/docs/s003/Suggett.pdf [accessed January 4, 2013].

TAC (Transportation Association of Canada), 1997. Determining the winter design temperature for asphalt pavements. Transportation Association of Canada, 46 p.

TAC (Transportation Association of Canada), 2010. Guidelines for development and maintenance of transportation infrastructure in permafrost regions (PTM-PERMAFROST), 8 p.

TAC (Transportation Association of Canada), 2011. Guidelines for construction and operation of winter roads (PTM-COWINDRD-E), 8 p.

TAC (Transportation Association of Canada), 2012. Climate change task force - October 2012 report. Transportation Association of Canada, 5 p., http://tech.tac-atc.ca/private/chiefengineers/pdfs/tomsc-att5-1012.pdf.

TAC (Transportation Association of Canada), 2013. Councils and committees - climate change task force. Transportation Association of Canada, http://tac-atc.ca/en/councils-and-committees/climate-change-task-force [accessed February 16, 2013.

Tarnocai, C., Canadell, J.G., Schuur, E.A.G., Kuhry, P., Mazhitova, G. and Zimov, S., 2009. Soil organic carbon pools in the northern circumpolar permafrost region. Global Biogeochemical Cycles, vol. 23, GB2023; doi:10.1029/2008GB003327.

Thompson, J., 2009. Minto flushes 300M litres of waste into the Yukon River. Yukon News, http://www.yukon-news.com/news/minto-flushes-300m-litres-of-waste-into-the-yukon-river.

Trochim, E. and Lipovsky, P., 2005. Alaska highway geotechnical borehole database: Beaver Creek to Kluane Lake. Poster submitted to Yukon Geoscience Forum 2005, http://www.geology.gov.yk.ca/pdf/ak_hwy_borehole_db_trochim_05.pdf.

UNEP (United Nations Environment Programme), 2012. Policy implications of warming permafrost, 38 p.

USARC (United States Arctic Research Commission) Permafrost Task Force, 2003. Climate change, permafrost, and impacts on civil infrastructure. Special Report 01-03, U.S. Arctic Research Commission, Arlington, VA, 72 p.

USACE (United States Army Corps of Engineers), 2006. Kivalina relocation master plan. US Army Corps of Engineers Alaska District, June 2006, p. 3, http://web.law.columbia.edu/sites/default/files/microsites/climate-change/files/Arctic-Resources/Relocation-Plans/USACE%20relocation%20plan%20Kivalina%20exec%20sum.pdf [accessed February 16, 2013].

van Everdingen, R., 2005. Multi-language glossary of permafrost and related ground-ice terms. National Snow and Ice Data Center/World Data Center for Glaciology, Boulder, CO, http://nsidc.org/fgdc/glossary/.

Water Canada, 2009. Nunavut gets flood relief. Water Canada, http://watercanada.net/2009/nunavut-gets-flood-relief/.

Water Resources Branch, 2011. Yukon water: An assessment of climate change vulnerabilities. Yukon Department of Environment, Government of Yukon, Water Resources Branch. http://www.env.gov.yk.ca/publications-maps/documents/yukonwater_climatechange_report.pdf.

Wei, M, Guodong, C. and Qingbai, W., 2009. Construction on permafrost foundations: Lessons learned from the Qinghai-Tibet railroad. Cold regions Science and Technology, vol. 59, issue 1, p. 3-11, file:///C:/Users/aperrin/Downloads/Ma-2009-Construction%20on%20perm.pdf [accessed December 10, 2012], doi: 10.1016/j.coldregions.2009.07.007.

Werner, A.T., Jaswal, H.K. and Murdock, T.Q., 2009. Climate change in Dawson City, YT: Summary of past trends and future projections. Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC, 40 p.

Yang, D., Zhao, Y., Armstrong, R. and Robinson, D., 2009. Yukon River streamflow response to seasonal snow cover changes. Hydrological Processes, vol. 23, p. 109-121.

Ye, H., Yang, D. and Robinson, D., 2008. Winter rain on snow and its association with air temperature in northern Eurasia. Hydrological Processes, vol. 22, p. 2728-2736.

YGS (Yukon Geological Survey, 2009. Alaska Highway Borehole Database. Yukon Geological Survey, http://ygsftp.gov.yk.ca/YukonPermafrostNetwork/AK_HWY_borehole_db_interim_release_March2009.pdf [accessed February 18, 2013].

Zdanowicz, C., Smetny-Sowa, A., Fisher, D., Schaffer, N., Copland, L., Eley, J. and Dupont, F., 2012. Summer melt rates on Penny Ice Cap, Baffin Island: Past and recent trends, and implications for regional climate. Journal of Geophysical Research: Earth Surface, vol. 117, issue F2, June 2012, doi: 10.1029/2011JF002248.

Zhang, T., Barry, R.G., Knowles, K., Ling, F. and Armstrong, R.L., 2003. Distribution of seasonally and perennially frozen ground in the Northern Hemisphere. In Proceedings of the Eighth International Conference on Permafrost, M. Phillips, S.M. Springman and L.U. Arenson, (eds.), A.A. Balkema, Zurich, Switzerland, p. 1289–1294.

Zhang, X., Hogg, W.D. and Mekis, E., 2001. Spatial and temporal characteristics of heavy precipitation events over Canada. Journal of Climate, vol. 14, p. 1923-1936.

Zhang, X., Vincent, L.A., Hogg, W.D. and Niitsoo, A., 2000. Temperature and precipitation trends in Canada during the 20th century. Atmosphere-Ocean, vol. 38, p. 395-429.

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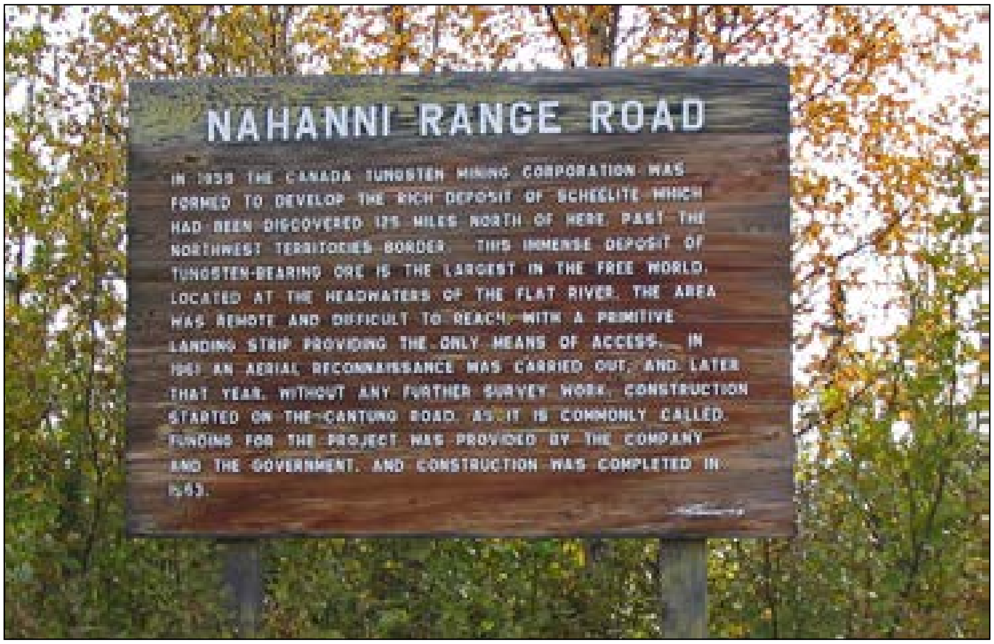
Where information was not available, guidance is provided in **bolded blue** text.

1. FORENSIC CASE STUDY 1: NAHANNI RANGE ROAD WASHOUT



1.1. Incident Overview

Date(s): June 12, 2012 **Location:** 61.4667°N 128.2719°W **Event Type:** Rain-on-snow, spring runoff, flooding

On June 12th, 2012, culvert washouts occurred at three different locations along the Nahanni Range Road in southeastern Yukon (CBC, 2012c). The mine road provides the only surface access for the Cantung Mine, and the event resulted in a multi-day shutdown of mine operations as well as the need for rapid, multi-agency effort to repair the washouts and re-establish the surface transportation route to the mine. There were several other locations in and around the Nahanni Range which suffered severe and damaging flooding during the late spring of 2012, including communities in parts of southwestern Northwest Territories (see Case Study 2) and northern British Columbia; flooding was the result of a ‘complex’ flooding event rooted in a combination of rainfall and rapid temperature increases causing rapid melt of the seasonal snow pack.

In the Climate and Infrastructure Forensic Analysis System (CIFAS), road washouts and/or culvert collapse during spring snowmelt or rain-on-snow events have already proven to be a relatively common occurrence in Yukon and Northwest Territories (17 out of 74 events in CIFAS). This type of failure therefore lends itself to a potential *cross incident analysis* when these events are analysed *together*, which could be the subject of future research.

1.2. Overview of Affected Infrastructure

This following section describes the general character of the affected infrastructure, including the following:

- **history–general significance, construction period, historical uses (e.g., including periods of abandonment)**
- **geographical situation, connections, nearby communities and facilities**
- **main owners, operators and users**
- **operations and management factors**

The goal of this section is to create a timeline for the construction, maintenance and use of the piece of infrastructure that was affected, as well as its significance to stakeholders. This will help focus subsequent sections and be used as a baseline for comparing the piece of infrastructure to climate and weather data, as well as begin the process of identification of potential sources of vulnerability.

The Nahanni Range Road, also known as Cantung Road, was constructed in the early 1960s and runs from the Robert Campbell Highway in northern BC, northeastward through the Mackenzie-Selwyn mountains to Tungsten in the NWT. The Nahanni Range Road follows a chain of lakes northeastward for 200 km to a tungsten mine in the NWT operated by North American Tungsten. Shortly after leaving the Robert Campbell Highway, the road cuts through a mountain pass at 7,000 feet of elevation, and follows the Hyland and Little Hyland rivers for most of the way to the Yukon-NWT border at Km 188. This route was long used by the First Nations in their seasonal travels to hunt and fish. The culverts that were washed out were mainly constructed during that time period, although some modifications were done at later dates (Abdulla and Suleman 2013; Figure 1).

Figure 1. *Washed out culvert on the Nahanni Range Road #1 (June 2012).*

The Nahanni Range Road is the only ground transportation link to the Cantung mine and is used to transport employees, fuel, supplies and critical materials for the mine. More than 100 miners, mill workers and exploration companies were out of work during the road closure. The first two-thirds of the gravel road was originally maintained by the Yukon government's Highways and Public Works (defined as 134 km by the Maintained Roads Inventory) while the other third was maintained by the Cantung mining company and was open to public traffic; however, there were no public facilities at the townsite. When the mine first closed in 1986, this portion of the road fell into disrepair and maintenance became increasingly difficult. Since the mine resumed intermittent production in 2003, the road has been restored for the use of the mining company, although general public travel is still not advised on this portion of the road.

1.3. Atmospheric Hazard Event

The following section discusses weather and climate components that contributed to the failure (e.g., flooding and its contributing factors, temperature and surface-water drainage in permafrost-related cases, etc.)

- **Use relevant meteorological and climatological measurements and visualizations, particularly when considering the timing of meteorological/climatological events that likely correspond to infrastructure incident.**
- **Discuss the data (e.g., distance of measurements from incident, quality control concerns, etc.), specifically its representativeness with respect to the incident, as well as the sources for particularly important data points.**
- **Consider measurements with respect to historical and climatological data and past conditions (e.g., magnitude of measurements of the incident compared to past extremes).**

****It is strongly encouraged that persons with climate or meteorological expertise be consulted for this section, particularly those with experience in assessing high-impact events.**

Typically, water levels on the Liard and South Nahanni rivers rise rapidly in the spring in response to snowmelt and rain-on-snow events. The winter of 2011-12 experienced unusually high winter snowpacks along with significant spring warming, leading to high water levels from snow melt. The snow course at Hyland River, for example, measured a snowpack at the end of April, 2012 that reached 238 mm water equivalent, which was more than twice the station's average value of 105 mm (based on a 36-year record). Temperatures had also warmed above 20°C from mid to late May – well above average.

Figure 2 illustrates the location of some of the meteorology and snow course stations that provide data for analyses in this complex terrain environment. Figure 3 illustrates the temperature and precipitation events that were observed at the Hour Lake station at the time of the rainfall and snowmelt flooding event. Note that rainfall amounts observed at Hour Lake were less than those that likely fell further east along the Nahanni Range Road and in the Logan Mountains.

The high water levels in early June, 2012 were further exacerbated by a significant rainfall event in early June, when more than 60 mm of rain was reported to have fallen in areas of record or near-record snowpacks. The only hydrometric station that was reporting at that time was the Hyland River station, where it appears likely that snowpacks were less extreme and rainfall amounts were also less than that observed along the Nahanni Range Road.

Figures 3 to 5 illustrate that the deep snowpack in conjunction with the high rainfall events that occurred in the spring of 2012, represent extreme weather conditions. As seen in Figure 5, the snowpack in the Nahanni Range Road region was measured at 130-150% of average conditions, as reported by a Yukon government hydrologist to the CBC (CBC, June 11, 2012). The only representative snow course available for the region is the Hyland River station, which reported a May 1 snow water equivalent value of 97 mm, which is a high but not extreme value for late April to early May. The heavy rain that fell from June 4-6, 2012 was also high for spring (e.g., 30 mm reported at the Hour Lake station). Newspaper articles and CBC reports and interviews (CBC, June 11, 2012) indicated that as much as 70 mm of rain fell at some locations during that time; however, data from other climate stations were not available to confirm this amount. As seen in Figure 4 at the Hour Lake meteorological station, the trend for annual maximum three-day rainfall events for any given month has been increasing (although not necessarily during the snowmelt season). Nonetheless, the damages were not surprising in light of the combination of a heavy rainfall in conjunction with a high snowpack during an unusually warm period. Such combinations of events are likely to become more frequent with future climate change.

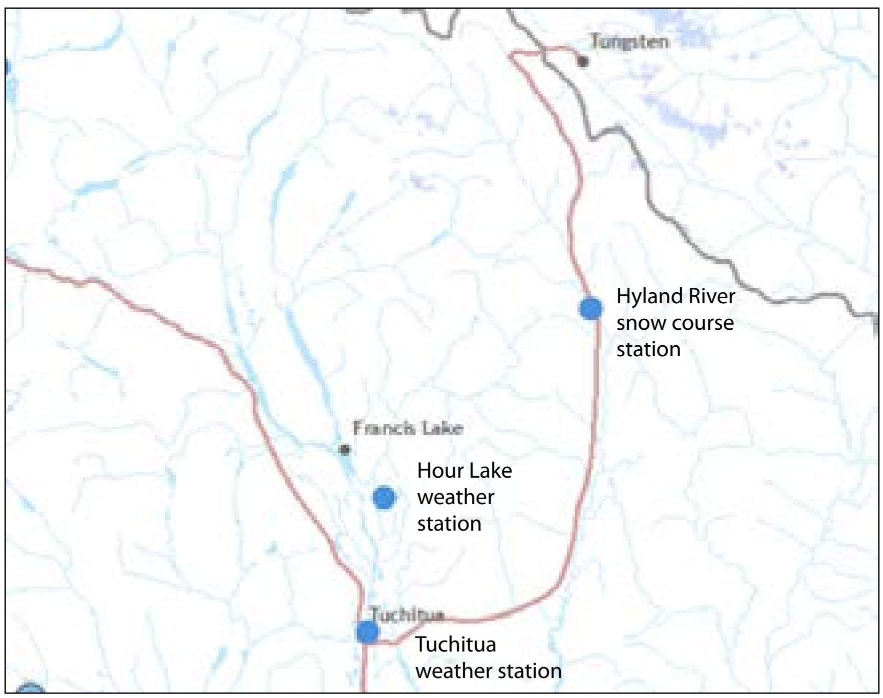


Figure 2. *Locations of meteorology and snow course stations in the region that recorded data at the time of the event.*

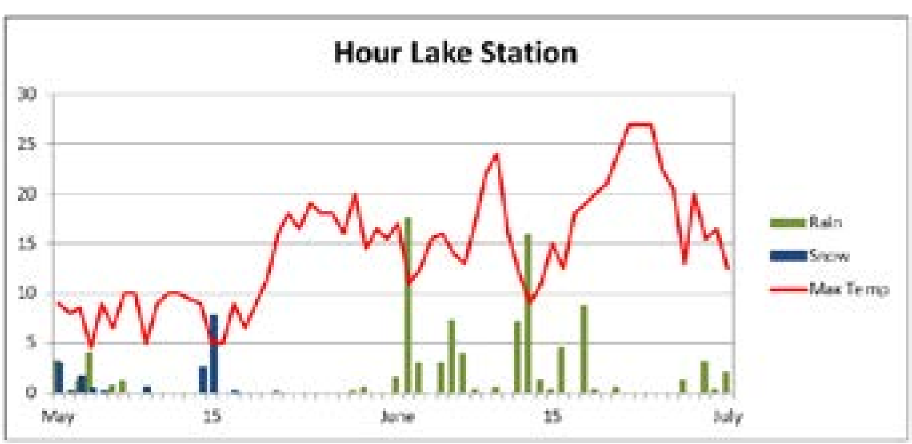


Figure 3. *Hour Lake meteorology station maximum temperatures (in °C) and daily rainfall and snowfall (in millimetres) for May and June, 2012.*

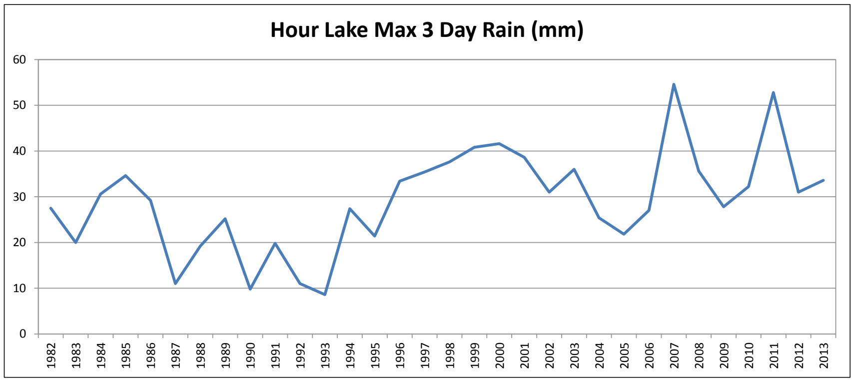


Figure 4. *Annual maximum three-day rainfall amounts for the Hour Lake meteorological station.*

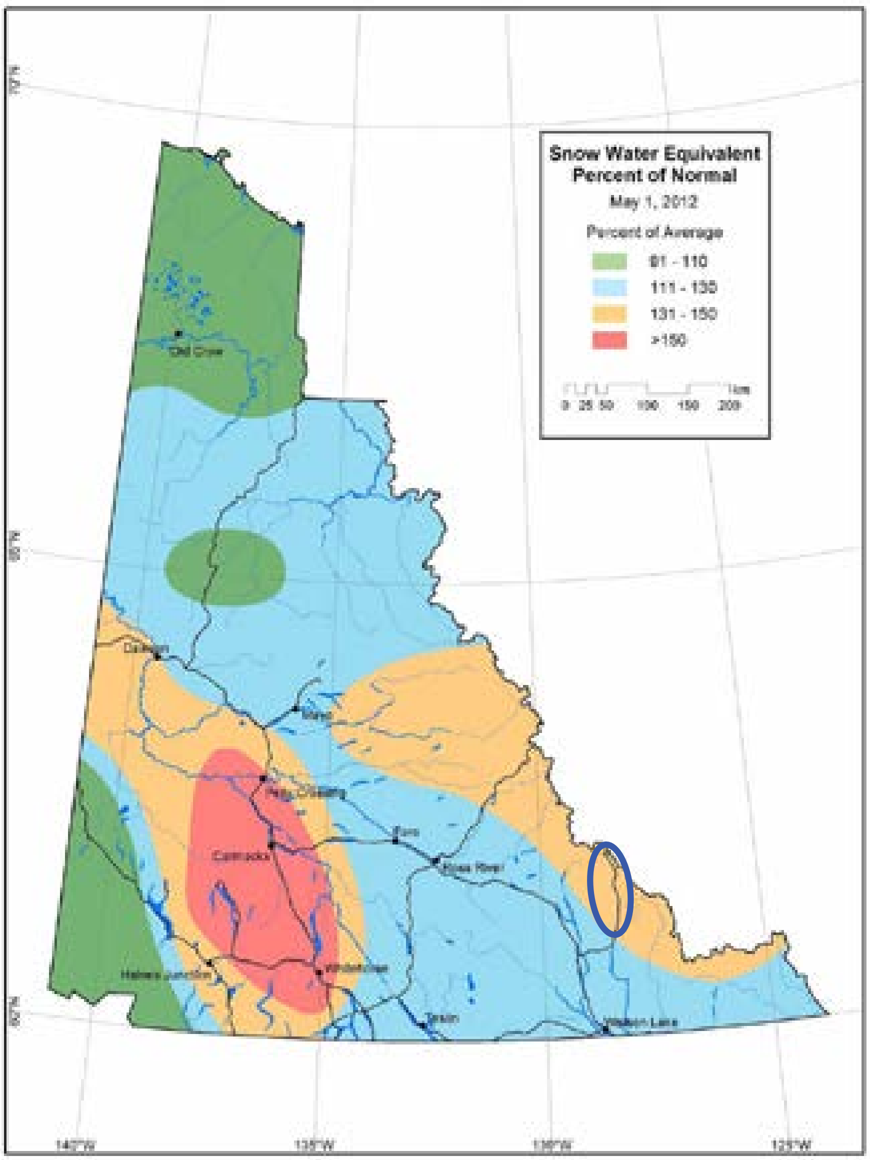


Figure 5. *Snow water equivalent analyses provided by the Yukon Government Water Resources Branch, Yukon Environment, for May 1, 2012. The blue highlighted ellipse denotes the study area.*

1.4. Engineering Considerations

Engineering considerations include all design elements relating to the type of loading associated with the incident, and include the following:

- **Review and identification of specific infrastructure and/or design elements which may have been related to the failure.**
- **Identify key guidance and design documents (applicable codes and standards), including and in addition to the following:**
  - **geometric design**
  - **geotechnical design**
  - **hydrotechnical design**
  - **mechanical design**
  - **electrical design**
  - **material specifications**
- **Provide description of load designs employed (return periods, specific design values for loads) and expected service life.**
- **Document siting, orientation, location of specific element.**
- **Report on materials used to make component.**
- **Provide any specific visual, anecdotal, or other data (including previous investigations) which could indicate particular engineering-related causes (e.g., visual information pre- and post-failure, corrosion or other material/bearing capacity losses/ weaknesses).**
- **Document indications of failure sequence.**
- **Provide component history (if different from that of larger structure).**
- **Supply role of all relevant components in incident (general description of role in failure or underperformance).**

If any relevant information is missing, make note of it and seek out additional information if needed. In some cases, though specific elements which were impacted and led to the failure may be (or at least appear to be) obvious, other elements should still be examined and considered. As with meteorological and climate data, information sources should be identified, characterized and discussed to provide proper context for forensic evaluation and data comparison.

****It is strongly recommended that this section be completed with the assistance and guidance of engineers and/or technicians with experience in designing, constructing and/or maintaining the type of infrastructure component(s) or element(s) affected in the incident.**

The design assumptions used for the original construction of the Nahanni Range Road are unknown, and given its age and date of construction, water crossings which employed culverts may not have been subject to flood design calculations (e.g., Gauthier et al., 2008).

Failures occurred at kilometre markers 38, 65 and 74, spanning river widths of 155, 30 and 130 ft (~47, 9, and 40 m, respectively; Abdulla and Suleman, 2013). Hence, each crossing represented different dimensions and design challenges.

In terms of failure sequence, two of the culverts that were depicted in photographs from source material (CBC 2012c; Abdulla and Suleman, 2013) clearly showed that after failure, these two culverts suffered the same mechanical failures. The inflow end of the culvert appears to have suffered plastic deformation by first being bent upwards and then flattened at the base, followed by total displacement. One photograph in particular (see left cover photo, Abdulla and Suleman, 2013), at a crossing in which only 1 of 4 culverts failed, shows soil deposits on what is assumed to be the *top* of the failed culvert, whereas there is no soil on the deformed portion. Hence, it is suggested (based solely on the visual information) that soil was first lost surrounding the inflow end of the culvert, water then bent and flattened the end until either, or both of the following occurred:

- the remaining soil surrounding the unexposed portion of the culvert was eroded from water that was diverted *around* the flattened inflow end instead of *through* the culvert; and/or
- the drag of the water against the exposed and deformed sections of the culvert generated enough force to overcome the shear strength of the remaining soil and/or soil-culvert interface (i.e., the shear plane was either within the soil or at the culvert/soil interface), and the culvert was washed out in one 'final' shear failure.

It is likely that a combination of both mechanisms generated failure, and characteristics of the soil surrounding the site could indicate which final stage resulted in ultimate failure (i.e., if either or both scenarios were contributors). Additional evidence is needed to corroborate or discount this failure sequence and/or its individual stages; however, it does provide a basis for determining potential design measures that could be implemented to reduce the risk of these types of failures occurring in the future.

Repairs made to the failed road sections used new, 'off-the-shelf' bridge components to replace 3 out of the 4 original culvert crossings, whereas a new culvert replaced the fourth crossing. Hence, replacement parts at the water crossings resulted in different infrastructure components (e.g., bridges instead of culverts in some cases), which should significantly reduce the future risk of failure.

The above section would be reviewed and completed by engineering experts from a multi-disciplinary team that would be required for the forensic analyses.

1.5. Responses to the Event

Description of responses to the event (e.g., reconstruction, emergency rescue, shut-down), including:

- **specific measures/actions taken (types of repairs, including new components and their characteristics); include any reasoning for specific choices (e.g., if new components differ from ones which failed);**
- **duration of disruption, monetary costs;**
- **effectiveness of measures taken (particularly if several years have passed since the incident); and**
- **participating/responsible agencies and companies involved (i.e., territorial or municipal governments, construction firms, mining companies, etc.).**

This section would significantly benefit from interviews with the first responders to the incident, or at a minimum, provide a collection of accounts from newspapers and other media coverage.

Fortunately, as a result of quick government and private sector responses, the road was reconstructed with a phased plan. The road was opened for restricted traffic in about one week – much earlier than expected – allowing miners, mill workers and exploration companies to get back to work with minimum delay and reduced losses to mine production.

The Yukon Government Highways and Public Works Department prepared and advertised a tender package for road repairs within 48 hours of the emergency situation (Abdullah and Suleman, 2013). Due to the inability to access the road, there were some unknowns about the necessary repairs; however, it was anticipated that extra work would be required and that many design decisions would need to be made on site during construction. Due to the time constraints, three predesigned, modular bridges were procured quickly to replace the three washed out culverts. The bridges were installed on temporary structures over an approximate one week period, allowing for the quick re-opening of the road to the public. All bridges were re-installed on permanent structures during the following two months, and are expected to have a 50-year service life. There were many additional challenges in repairing the road and installing the bridges which included the following: no crane was locally available for girder placement; the contractors were inexperienced in constructing bridges of this size; the timelines were extremely short; local and easily available materials needed to be used; major erosion issues needed to be addressed; and finally, construction took place under risky and fast moving water conditions.

1.6. Forensic Analysis: Determination of Cause and Uncertainties

This following section uses analyses and the combining of data to determine the cause(s) of failure based on the sections described above. It cannot be automated, hence instructions are provided for the execution.

By combining and comparing the information and analyses described above, the likely causes of failure can be determined. Examples may include:

- **Were design values exceeded? Or is there reason to believe failure occurred prior to those values being exceeded? If yes, why?**
- **Do concerns exist regarding *data quality* or *representativeness* that may cast doubt on the results of the forensic analysis? What data would be needed to confirm or eliminate any hypotheses developed in the analysis?**
- **Be critical of any single-cause hypotheses, this includes critical evaluation of any previous investigations, which may require follow-up on sources of, and reasoning for, conclusions in previous work.**
- **Determine the final suite of climate/weather elements which were most likely related to the failure and which will be subject to trend and projections under the next section**

Findings from this section are then used to begin developing recommendations and adaptation options that address already existing risks and sensitivities. This section should be used in conjunction with the following section on future trends (including uncertainty in those trends) to develop climate change adaptation plans.

The meteorological assessment appears to indicate that heavy rainfall and rapid snow melt at higher altitudes were the main contributors to the high flow conditions. The snowpack conditions at the Hyland River station (the final measurement taken on May 1st), show that seasonal snowfall totals were very significant; however, measurements taken in the valley bottom are not necessarily indicative of the amount of snowpack at higher altitudes. Photographs of the failed culverts clearly show that snow in the immediate surrounding area was gone at the time of the incident (CBC, 2012c).

Design values for the original culverts may be difficult to determine. As indicated by Gautier et al. (2008), culverts of this age were not subject to design calculations for river flows. Hence, the dimensions of the original culverts as well as the site conditions would be required in order to determine what their maximum flow capacities were. There were also undefined ‘modifications’ that were completed following construction in the early 1960s that were not documented.

Abdulla and Suleman (2013) indicated that the new infrastructure was designed and built to CSA standards and for a 50-year design life; however, they also note that a site survey, geotechnical analysis, hydraulic analysis, and "proper design work" were not performed due to the tight time schedule and the pressure to re-open the road as quickly as possible. To their credit, the new bridges clearly allow for more unobstructed flow than the original culverts, but it is not known if hydraulic calculations, such as maximum allowable flood level, have since been conducted to determine if the bridges are sufficiently designed for unusually high or even extreme spring freshets. For example, what are the maximum flow rates that the new bridges can withstand, and how do they compare to the spring 2012 event or others which could occur in the future?

Salvaging the remaining culverts for future use, however, suggests that at least the culverts themselves were in working condition (e.g., no obvious corrosion or deformation; Figure 6), and hence soil erosion around the culverts appears to be the most likely cause of the failures.

Figure 6. *The Nahanni Range Road, which leads to the mine, was washed out in three locations; however, the culverts displayed no obvious corrosion or deformation (Yukon Department of Highways and Public Works).*

To conclude, there are still two key elements are missing which prevent quantitative analysis: 1) the flow experienced by the failed culverts during the event; and 2) the maximum allowable flow for the new infrastructure. However, some indications suggest that culvert failure was due to extreme water flows, and given that the culverts sustained over 50 years of good working condition, the 2012 spring flow event likely represented an extreme water volume which exceeded the design capabilities of the culvert crossings. This also correlates well with the meteorological data, which indicated an extreme snow pack as well as significant rainfall in conjunction with unseasonably warm temperatures.

The discussion above is for *illustrative purposes only,* and is based solely on the currently available data and which may be incomplete.

1.7. Climate Trends, Climate Change Projections and Future Risks

The following section describes relevant climate trends based on past and recent climate data, as well as future projections for *relevant* climate elements and indices. This will include both the raw output from the most current climate models, as well as any specific research conducted on similar hazards (e.g., using statistical downscaling, earlier generation models). The results are contrasted and compared and any uncertainties of trends and values are discussed as follows (future versions of this product will contain more methodical guidance on how to obtain and interpret climate data and projections for the purposes of analysis):

- **Do recent trends conflict with climate change projections?**
- **Do previous studies conflict with recent trends?**
- **Is the contributing weather/climate element complex and does it require more detailed analysis?**
- **Is there significant variability in climate change projections, including trend direction? Is the uncertainty significant enough to affect a required adaptation response based on the sensitivity of the infrastructure (i.e., relative to its 'breaking point' or known climate thresholds)?**

Complete this section by describing the most likely changes and their magnitude, as well as the level of uncertainty, for future risks.

****It is strongly suggested that this section be completed with the assistance of an individual with climate expertise, particularly in relation to the use of climate change projections and analyses of historical climate trends.**

1.7.1. Past and Recent Trends

As is illustrated in Figure 3, three-day maximum rainfall amounts have been increasing over the past decade at the Hour Lake station. Temperatures, especially in winter and spring, have also been increasing and would contribute to more rain-on-snow events (see Figure 5 for temperature trends, and Figure 7 for daily mean temperatures for winter and spring). Furthermore, at the Hyland River snow course station, while the winter snow cover season has been shortening, the annual maximum snow water equivalent values have been increasing over the last several years (Figure 8). Given that late winter to spring precipitation amounts are expected to increase into the future, and average temperatures will remain below freezing from December to April, it is likely that extreme snowpack conditions may also increase in the region. Additionally, current research indicates that spring snowmelt has been occurring earlier over the last several years.

A recent study of streamflow runoff trends in northwestern Canada indicate increases in annual and winter runoff amounts for the Liard and Nahanni river basins in southeastern Yukon to southwestern NWT (Bawden, 2013). The analyses, shown in Figure 9, indicate statistically significant (10% levels) increases in annual and winter runoff values for the Logan Mountains drainage basin.

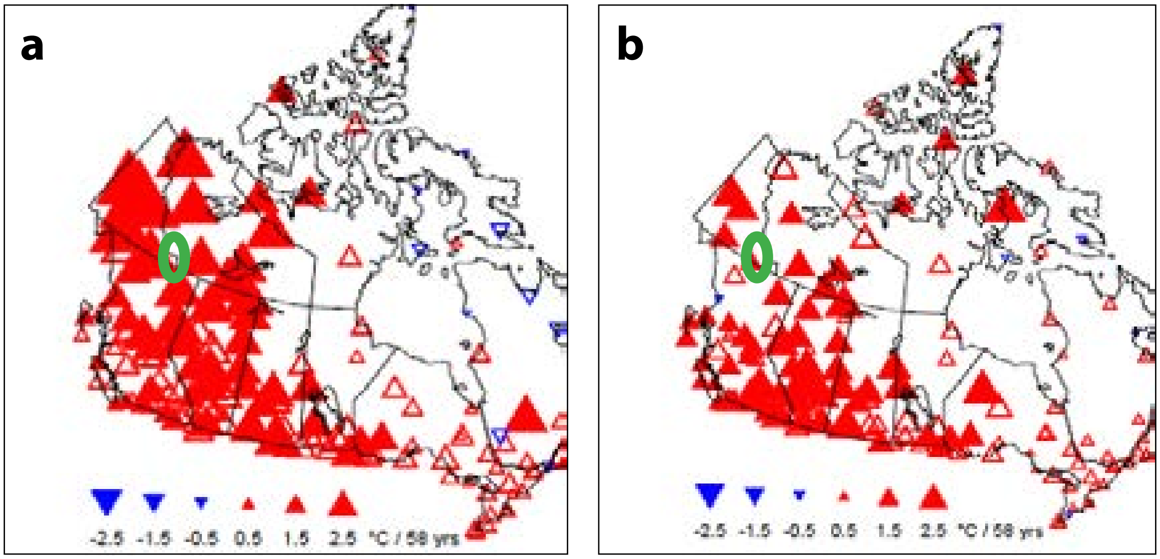


Figure 7. *Observed trends in daily mean temperatures for* ***(a)*** *winter (Dec-Feb) and* ***(b)*** *spring (Mar-May) for Canada for the time period 1950-2007. The Environment Canada analysis uses homogenized or normalized climate station data to remove non-climatic influences on temperature trends. The areas of interest are shown in green highlight. (Analyses from Mekis and Vincent, 2008.)*

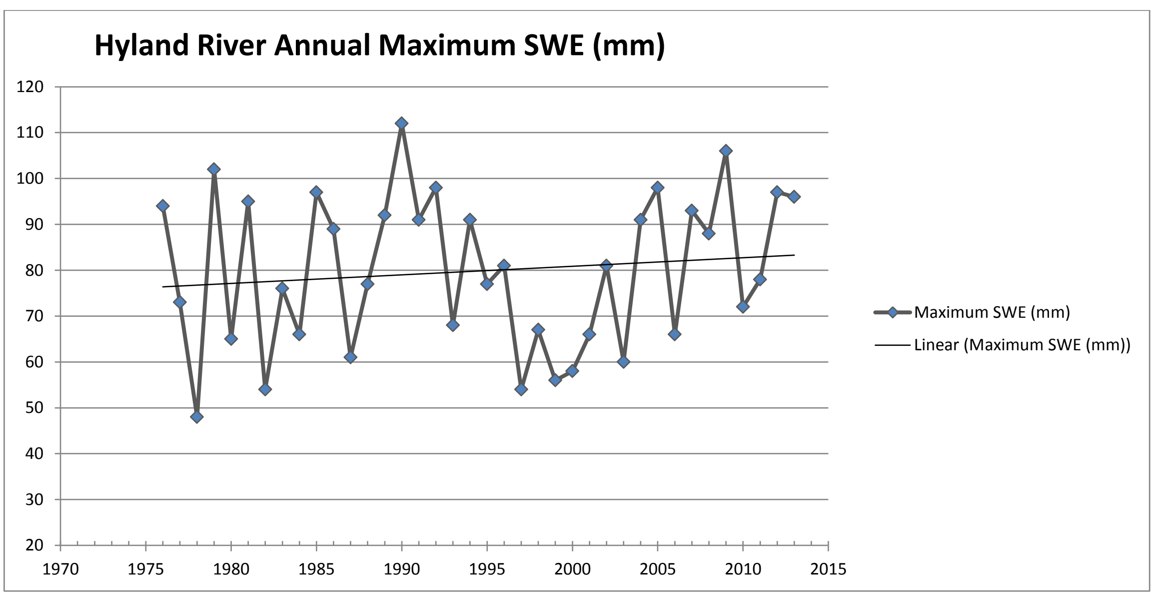


Figure 8. *Annual maximum snow water equivalent values for Hyland River, Yukon, for the time period 1976-2013.*

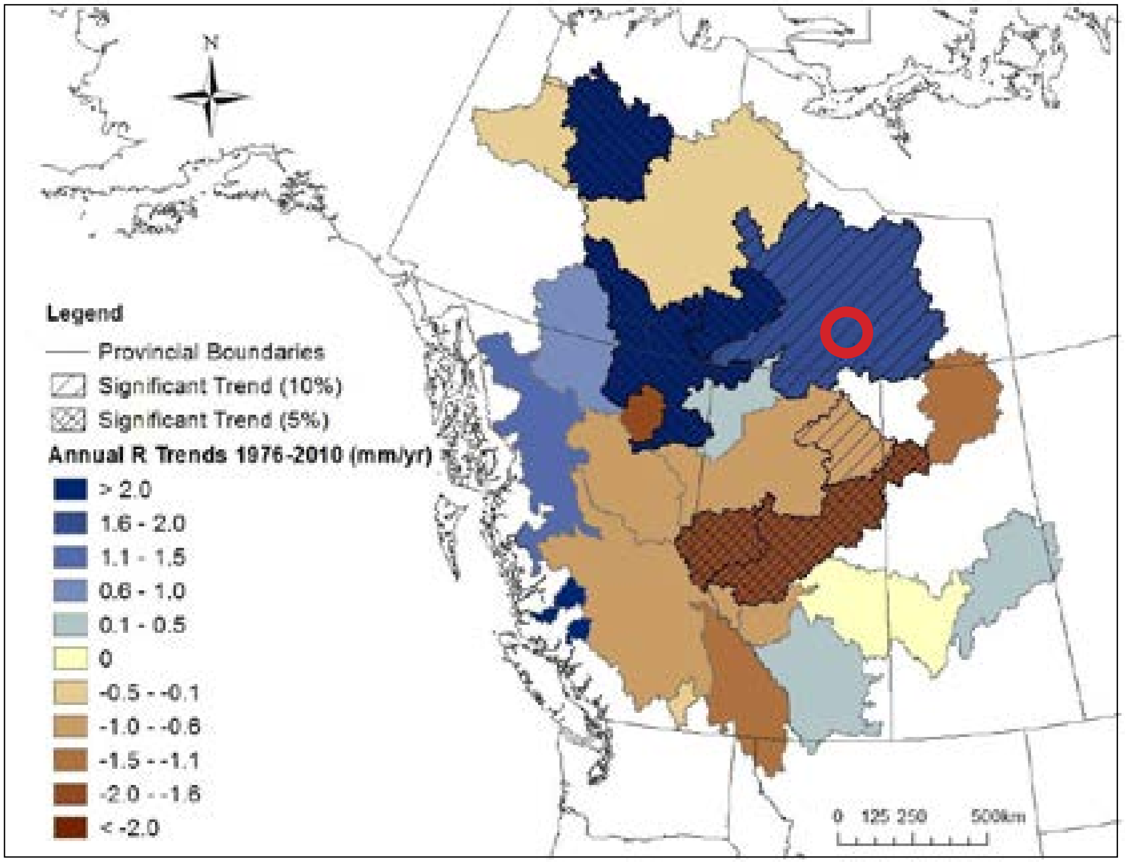


Figure 9. *Map of annual runoff trend slopes for the 1976-2010 analysis period. Basins exhibiting significant trends are illustrated with hatch and line patterns (Bawden, 2013). Study area is delineated with red outline.*

1.7.2. Climate Change Projections

As spring temperatures and precipitation amounts continue to rise, it is likely that the Nahanni Range Road region can expect more rain-on-snow events at the time of the spring snowmelt. Figure 10 illustrates projected trends for an ensemble of the IPCC AR5 climate change models. The results indicate that the amount and rate of spring warming and precipitation increases that can be expected into the future to the 2080s (2070-2100) are strongly dependent upon the continual rise of accumulated greenhouse gases (GHGs). The future GHG assumptions are captured by the Representative Concentration Pathway (RCP) 4.5 curve indicating moderate decreases in global greenhouse gas emissions, and by the RCP8.5 contour for limited reductions in total GHG emissions into the future. The results are shown for a grid point that includes the Nahanni Range Road. As shown in Figure 10b, for the higher GHG emission assumptions (red curve, RCP8.5), the future warming will be greater and faster; the blue line (RCP4.5) illustrates the warming that is expected under significant GHG emission reductions. In reality, current global GHG emissions are trending closely to the RCP8.5 assumption and dramatic global reductions in GHG emissions would likely be required to reach the RCP4.5 assumption in the future.

Spring is typically defined as including the months of March-April-May; however, for the Nahanni Range road region, these months represent late winter and currently correspond to the time of maximum snowpack and the start of snowmelt. While it is more difficult to detect trends and to project future trends for precipitation, Figure 10b points to ongoing increases in spring or late-winter total precipitation into the future. Figure 11a demonstrates the projected percentage increases in annual precipitation from the 1981-2010 climate normals under low and high GHG emission assumptions (i.e., RCP4.5 and RCP8.5, respectively). Figure 11b indicates that the greater change from the 1981-2010 climate normals is the increase in the one-day maximum precipitation value rather than the annual mean precipitation, highlighting the potential for more intense rainfall events in the future. When coupled with warming temperatures, it is likely that increased winter precipitation may result in greater snowpacks in some years along with increased frequencies of mixed precipitation or rain-on–snow events. It is important to note that while some projections show average winter snowpacks in this region decreasing, the trends in the extremes of these snow conditions or snowpacks may increase. Note that trends in extreme precipitation values can differ significantly from trends in average annual precipitation values.

a **b**

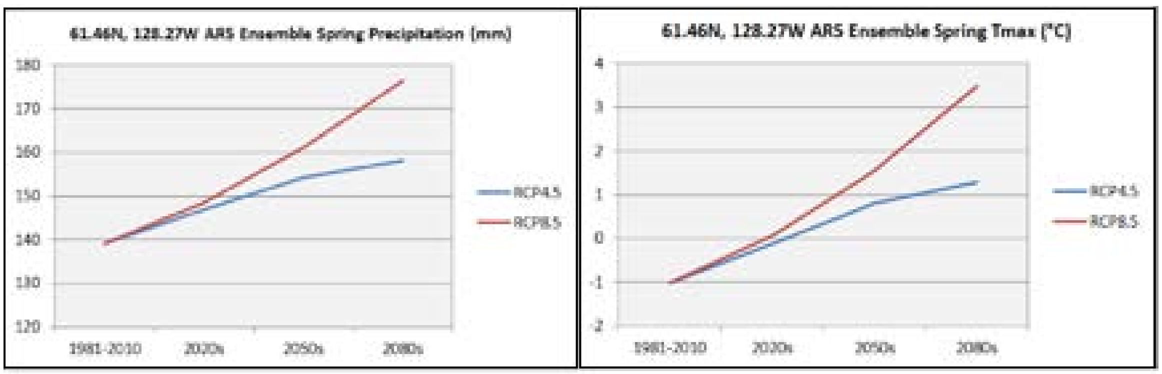


Figure 10. *IPCC AR5 (IPCC, 2013) projections of* ***(a)*** *spring or late winter precipitation and* ***(b)*** *maximum temperatures for the grid cells that includes the Nahanni Range Road.*

a **b**

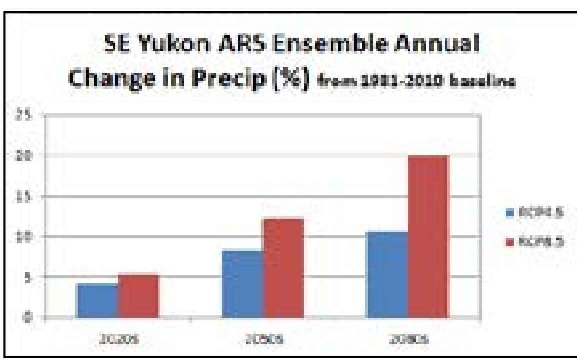


Figure 11a. *IPCC AR5 (2013) ensemble (all climate models) projections of per cent changes to annual precipitation compared to 1981-2010 interpolated values (from Risk Sciences International).*

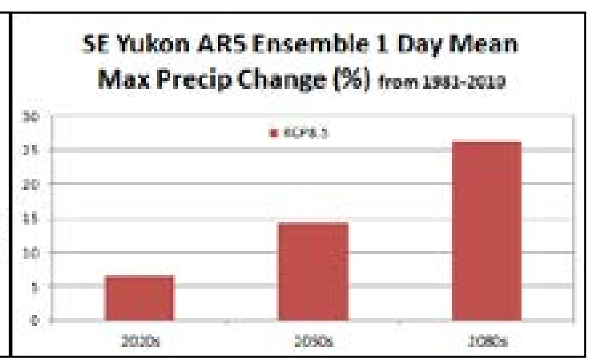


Figure 11b. *IPCC AR5 (2013) ensemble (all climate models) projections of per cent changes to one-day maximum precipitation compared to 1981-2010 interpolated values (from Risk Sciences International).*

1.8. Adaptation Actions and Recommendations

After having evaluated the contributing factors and causes of the failure, characteristics of the response, combined with an assessment of future risks, specific recommendations and adaptation actions can be defined.

- **Define the strengths/weaknesses in construction and/or design and implications for codes and standards, up to and including generating new clauses or amending current ones.**
- **Determine the strengths/weaknesses in maintenance or response and how to use them/address them through the responsible organizations or authority.**
- **Define the strengths/weaknesses in meteorological/climatological monitoring and dissemination, and identify those changes which would improve response, forecasting, and operational planning, etc., in the future.**
- **'Flag' design or maintenance indicators (e.g., periods of abandonment, age of infrastructure) which could identify other similar 'at-risk' pieces of infrastructure.**
- **Identify climate 'breaking-points' or thresholds and their antecedent conditions, which can be used in conjunction with forecasts and monitoring to help anticipate an event.**

This section is designated for the generation of actionable statements with the goal of risk reduction for current and future operations.

The event that washed out sections of the Nahanni Range Road in the spring of 2012 was the result of coincident heavy snowpacks, extreme spring rainfalls, and abnormally warm temperatures. These types of spring extremes are likely to continue to increase in intensity and frequency into the future. It is becoming increasingly important that climate and snow course data coverage be sufficient to allow the early detection and warning of these coincident or 'perfect storm' conditions, particularly given the complex terrain that exists in much of Yukon. While the Government of Yukon currently maintains excellent climate and snow course data networks relative to many other regions in Canada, this forensic analysis was still limited in its ability to analyze the severity of the climate conditions due to a shortage of representative data. It would also be beneficial to develop snowmelt and rain-on-snow models that are representative of Yukon's regional climate conditions and varied terrain in order to reflect the risks associated with extreme rainfall events that occur in conjunction with peak snowmelt.

Climate change projections also suggest that these increases in spring runoff extremes will require increased emergency management planning along with enhanced reconstruction practices to deal with potential impacts of these events on existing, aging and increasingly vulnerable infrastructure. The risks to the existing infrastructure would be well informed by the development of vulnerability and risk assessments, such as those offered through the Engineers Canada PIEVC process. Ongoing maintenance practices and budget processes will need to include timely responses to impacts from more frequent winter and spring runoff events on transportation infrastructure; that is, enhanced maintenance will be needed to reduce the risks of more road failures. Maintenance and recovery practices need to consider the importance of rapid response when critical transportation links are disrupted and where there are no reasonable alternative transportation options. New infrastructure projects will also need to consider the increase in extreme climate events and their associated risks while in the design and maintenance phase.

Fast and effective responses to repair the washouts on the Nahanni Range Road involved many challenges that included: the need for rapid repair; the remote location of the road; the challenging terrain; the many unknowns about the required reconstruction; an inexperienced contractor; the need for local and easily available materials; the lack of access to a crane for bridge replacement; and the need for construction to take place under risky high water-flow conditions. The challenges were met, and the road was successfully reopened to traffic in about one week, resulting in miners, mill workers and exploration companies able to go back to work with minimum delay. Given the increased risks for similar washout conditions occurring in the future, the Yukon Highways and Public Works Department feels that they have an emergency response plan that is able to deal with the situation in a safe and professional manner (Abdullah and Suleman, 2013). It is important that infrastructure managers consider emergency response planning, budgets, and preventive maintenance when addressing the many challenges that will arise with future road washouts, particularly when there are no alternative routes.

1.8.1. Recommendations

A small number of design suggestions are provided for *illustrative purposes only*; recommendations should be reviewed by other experts.

Based on the findings of the analysis, list suggested actions relating to:

- engineering design (load increase, additional design features)
- reinforcement on inflow end of culverts to reduce potential for plastic deformation
- erosion reduction measures for soils surrounding inflow portion of culvert
- monitoring systems to indicate when rapid erosion is taking place, particularly in soil on inflow end of culverts
- emergency relief or other sacrificial design elements could be installed, specifically using new flow volume calculations determined from recent extreme events and guided by climate change projections and trend information; such design elements should significantly reduce required repair time and cost
- management (actions which could prevent time sensitive, aggregate effects; indices or indicators)
- generate inventory of water crossings for mine roads which have been subject to multi-year abandonment and/or which have been in service for over 25-30 years
- Abdullah and Suleman (2013) indicated a lack of experience among contractors with regards to large bridge construction; mines should therefore consider the particular expertise needed for repair of critical infrastructure components and identify potential service providers
- climate/weather information needs (event types or specific forecast elements needed to decide on actions)
- consider a combination of year-end water course snow pack monitoring with daily weather monitoring and forecasts; ‘total’ available flood water should be considered, with systems in place to communicate this information to stakeholders (include indications from nearby extreme events, such as Nahanni Butte flood which occurred 3 days prior to the Nahanni Range Road incident)
- for forecast and warning systems that may already be in place, improve dissemination, or possibly integrate flood forecast information in mine operations planning
- Other: components specific to the piece of failed infrastructure, affected stakeholders, etc.

2. FORENSIC CASE STUDY 2: NAHANNI BUTTE EVACUATION AND ROAD FAILURE

Figure 12. *Water from the South Nahanni River flooded the majority of Nahanni Butte as seen in this photo taken on June 12, 2012. Photo courtesy of Wilbert Antoine.*

2.1. Introduction

The community of Nahanni Butte is located on the banks of the South Nahanni River approximately one kilometre up river from the confluence of the Liard and South Nahanni rivers (shown in red shading in Figure 13). The Liard River is a tributary of the Mackenzie River. Nahanni Butte is located 23 km west the Liard Highway (Hwy #7) and 95 km north of Fort Liard. A 23-km, all-season road was opened from the Liard Highway to the shore of the Liard River across from Nahanni Butte in 2010. Access to the community of Nahanni Butte in summer is by water taxi across the Liard River and by ice road in the winter (see Figures 14a,b). The new road picks up again on the other side of the Liard River. There are no plans for a vehicle ferry. Nahanni Butte is situated in a discontinuous permafrost zone and little to no permafrost has been documented in this region.

Figure 13. *Community of Nahanni Butte shown in pink shading and located near the confluence of the Liard River and South Nahanni River.*

Figure 14a. *Highway #7 and the community of Nahanni Butte.*

Figure 14b. *A new 23 km, all-weather access road was opened to Nahanni Butte in 2010 and runs from Highway #7 to the east bank of the Liard River. A water taxi crosses the Liard River in the summer, and an ice road is used in winter, and then the access road continues to the community of Nahanni Butte.*

2.2. Infrastructure Failure: Flooding

On June 8th, 2012, rising water levels in the Liard and South Nahanni rivers created a flood-risk for the communities of Fort Liard and Nahanni Butte. Water levels in the river continued to rise, overflowing its banks and reaching low-lying areas of Nahanni Butte, leading to an evacuation of the community. The majority of the residents were evacuated: 52 people were evacuated by plane to Fort Simpson; another 16 were transported by helicopter across the river to personal vehicles to find other temporary residences; and approximately 21 people remained in the community. Residents started to return home to Nahanni Butte three weeks after evacuation.

The flooding damaged 11 homes in total, which is a relatively sizeable proportion of the total housing stock. Other damage assessments made by the NWT Government on June 18th indicated that various community infrastructure, including communication and water treatment facilities, were also damaged. Due to the effective emergency response actions and coordination by the Department of Municipal and Community Affairs, there was fortunately no loss of life.

Flooding occurred as a result of a 'perfect storm' event, that is, the combination of a heavy spring snowmelt, unseasonably high spring temperatures, and an abnormally heavy spring rainfall.

2.3. Responses to the Event

Responses to this emergency were coordinated through a number of agencies, including the community government of Nahanni Butte, the GNWT, Government of Canada and RCMP. After the evacuations, the first priority of crews responding to the flood disaster was to reduce water levels at the airstrip so airplanes carrying materials for repair and reconstruction could land safely. The crews then turned their attention to the pools of water in and around the community, and used pumps and newly dug trenches to channel and divert the water back into the river.

In mid-August of that same year, a meeting with the Premier and Territorial Ministers prompted further actions to be made to reduce the many impacts from the June flooding event, including disaster financial assistance. One of the several impacts to the community included the flooding of parts of the access road which was submerged under approximately a half metre of water and was only accessible for larger trucks using a marked path through the water (Figure 15). Community residents travelled over the submerged parts of the access road using large trucks and boats. A couple of options were put forth to deal with the flooded roadway: 1) build the road base higher; and 2) dig a drainage ditch to redirect the water back to the river. It was determined that the ditch option would be too costly and would require significant permitting since the ditch would need to be approximately four metres deep and two kilometres long (Northern News Service, August 15, 2012a,b,c). Therefore, repairs to the road and drainage were delayed until the winter road season.

Figure 15. *Parts of the access road to Nahanni Butte were under water throughout the summer and fall of 2012. Photo courtesy of CBC News.*

Upon their return, the community took on several additional actions. The Nahanni Butte Dene Band of the Dehcho First Nation, in collaboration with various territorial government departments, developed an updated emergency response plan, which they claimed to be almost bulletproof. The community also developed a new drainage plan, and planned road upgrades to sections impacted by the flooding, including the installation of new culverts as well as raising the level of the roadbed.

The community has also discussed the feasibility of moving the entire town across the Liard River to higher ground over concerns that the Liard River may flood again after repairs are completed.

2.4. Engineering Considerations

The design assumptions used for the construction and reconstruction of the Nahanni Butte access road and community drainage are unknown. Any reconstruction could benefit from further analyses of the chances of similar snowmelt and rainfall conditions recurring.

This section and completion of the forensic analysis would be carried out by engineering experts from a multi-disciplinary team.

2.4.1. Climate Factors

Annual spring break-up in the southern Mackenzie and Liard rivers usually begins in April and lasts for about 10 weeks. Typically, water levels on the South Nahanni and Flat River watersheds increase rapidly in the spring in response to snowmelt and rain-on-snow events. It was the combination of rapid snowmelt and an extreme rainfall that spring of 2012 that triggered the flooding event.

Although there are no available data for snowpack or snowfall measurements for the winter and spring of 2011-12 in the vicinity of the study area, observations from a snow course station on the west side of the Mackenzie Mountains indicated that snowpacks were very high. Thawing was rapid due to temperatures that were significantly higher than average in the period from late May into June, 2012. Two climate stations in the watershed reported significant precipitation values from June 6-11 totalling 87-91 mm of rain; on June 10-11 alone, the total rainfall amounted to 55-60 mm. Furthermore, this extreme precipitation coincided with spring rising water levels.

Fortunately, some water level and flow data was available for local streams at the time of flooding. Observations from the Environment Canada gauge station of South Nahanni River to the north (and just above Virginia Falls) showed that water levels in the South Nahanni River peaked at approximately 5.9 m on June 13, just 0.04 m shy of the record high (recorded data is from 1962 to present; see Figure 16). The gauge station also recorded its third highest annual maximum daily discharge (see Figure 17). At the Fort Liard station on the Liard River, levels peaked at approximately 10 m on June 11, just 0.22 m short of the record high; this value also coincided with the highest annual maximum daily discharge reported in 68 years at this station. A record was also broken at the mouth of the Liard River (at Flat River), where the water peaked at 9.58 m on June 13, 0.87 m higher than the previous record of 8.71 m on June 6, 1977 (see Figures 18 and 19).

Although it is unusual for this combination of extreme events to occur concurrently, they are expected to occur more frequently as the climate of the region continues to warm and the extreme snowpack conditions continue to increase into the future.

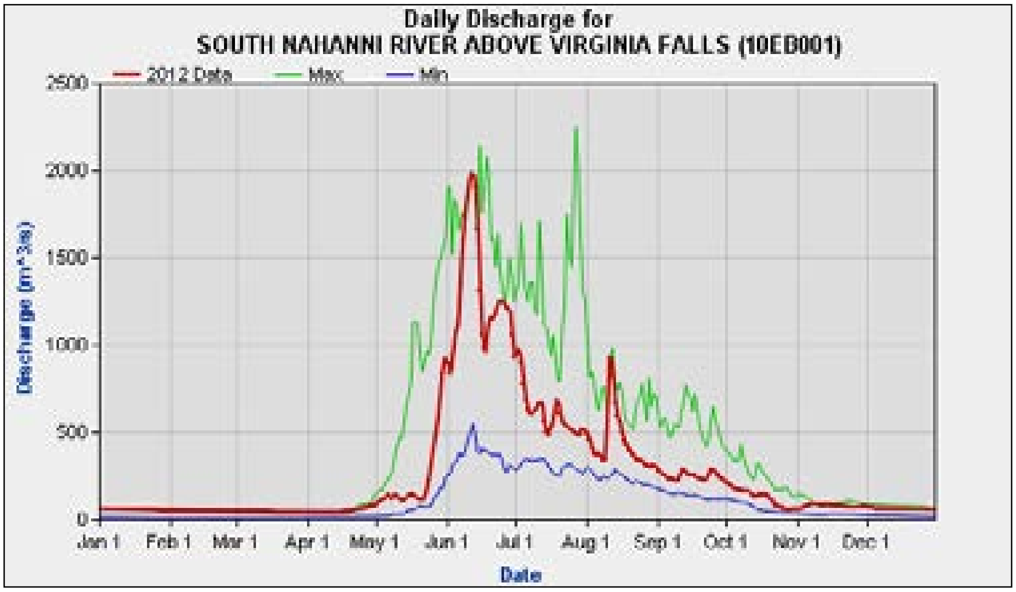


Figure 16. *Statistical comparison of the 2012 daily averaged discharges to maximum daily discharges observed over a 71-year period from 1942 to 2012 at the 'South Nahanni River above Virginia Falls' gauge station.*

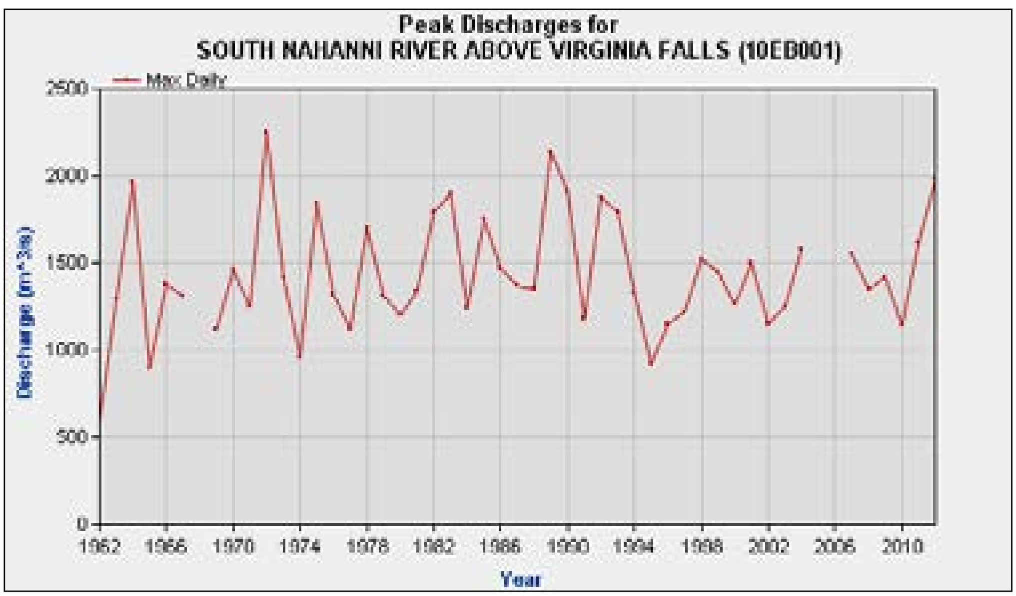


Figure 17. *Maximum daily discharges observed over a 51-year period from 1962 to 2012 at the 'South Nahanni River above Virginia Falls' gauge station.*

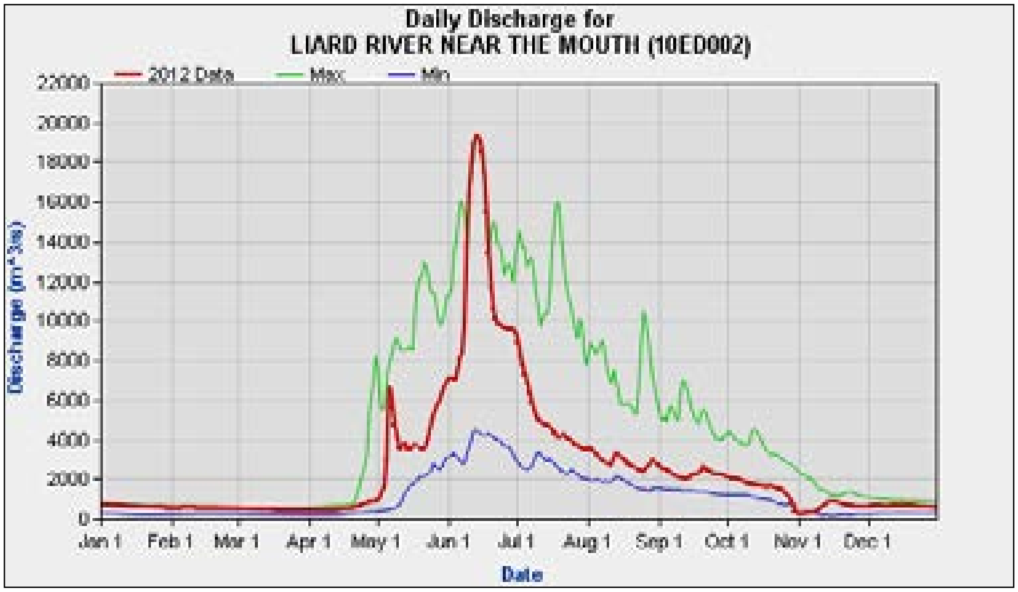


Figure 18. *Peak daily discharges for the 'Liard River near the mouth' gauge station for June, 2012 compared to annual maximum (peak) daily discharges for the 41 years of data recorded from 1972 to 2012.*

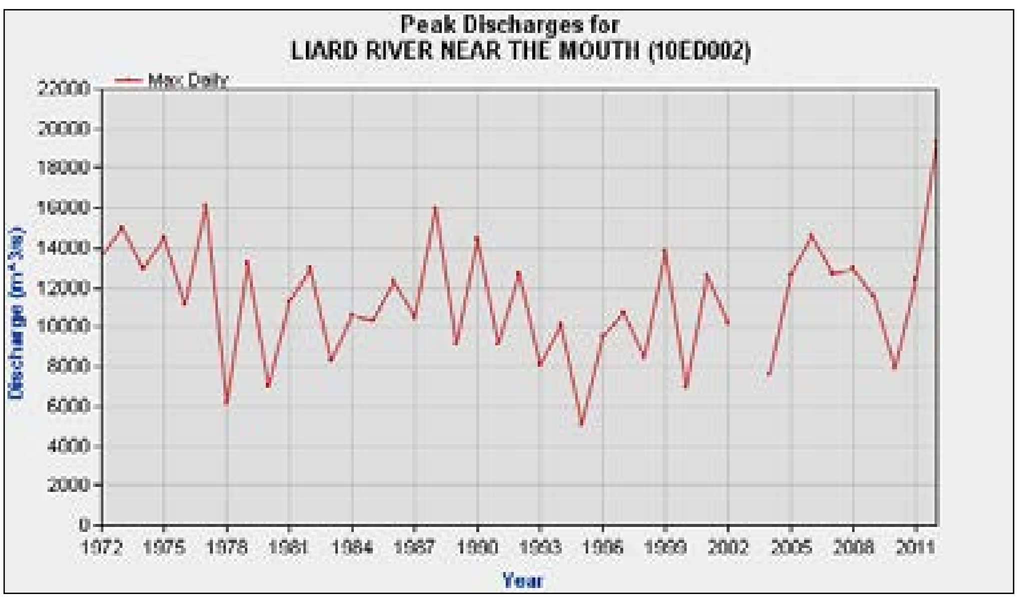


Figure 19. *Statistical comparison of the 2012 daily averaged discharges for the Liard River near the mouth gauge station compared to annual maximum daily discharges for the 41 years of data recorded from 1972 to 2012.*

2.5. Climate Trends, Climate Change Projections and Future Risks

Temperatures, especially in winter and spring, have been increasing in the Nahanni Butte region (see Figure 20). The increases in annual minimum temperatures have been greater than those changes observed in annual maximum and average temperatures. That is, cold season (winter, spring) temperatures have been warming at a significantly greater rate than the traditional warm season temperatures.

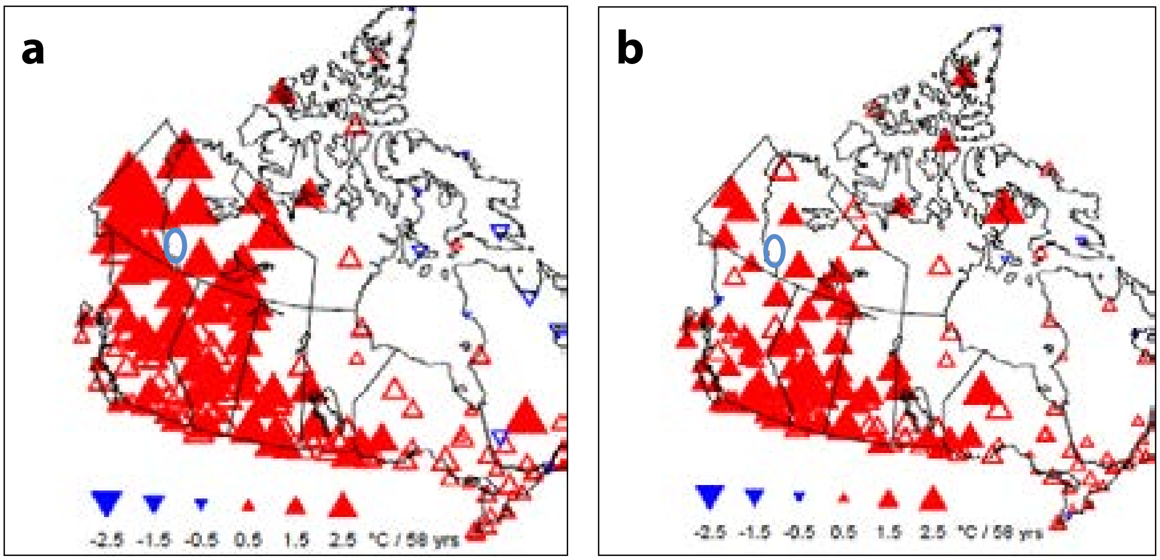


***Figure 20.** Observed trends in daily mean temperatures for **(a)** winter (Dec-Feb) and **(b)** spring (Mar-May) for the time period 1950-2007. The Environment Canada analysis uses homogenized or normalized climate station data to remove non-climatic influences on temperature trends (from Mekis and Vincent, 2008). The areas of interest are denoted by blue elipses.*

While the winter snow cover season is generally shorter in most southern Arctic regions, the extreme snowpack amounts in some years have been tending towards increased snow depth and snow water equivalents (see Figures 21a, b, c). Snow water equivalent data was not available for the region for 2012, but snow data from Yukon Water (Government of Yukon, 2013) for the Hyland River station on the west side of the Mackenzie Mountains indicates an increasing trend, as shown in Figure 21a. Seasonal snowfall amounts, which are represented by the accumulated day-to-day snowfall measurements over the cold season, are available for the Fort Simpson climate/weather station and show increasing trends (Figure 21b). Note that the year-to-year variability in the amounts is large and that the heavy snowfall years have become more common over the past decade. It is difficult to assess any trends in the snow water equivalent from the snow course measurements at Fort Liard as data is lacking; however, the measurement from the winter of 2012-13 indicates a new record value for the measured dataset (see Figure 21c). While average snowpack conditions may be decreasing in many northern regions, trends in extreme conditions often show opposite trends (i.e., increases).

Given that cold season precipitation amounts are expected to increase into the future, it is likely that extreme high snowpacks may increase with large variability expected as conditions range from very low to very high snowpacks.

One analysis of streamflow runoff trends in northwestern Canada (shown in Figure 22), indicates increases in annual and winter runoff amounts for the Liard and Nahanni river basins in the southeastern Yukon to southwestern NWT region (Bawden, 2013). The analyses indicate statistically significant (10% levels) increases in annual and winter runoff values for these drainage regions.

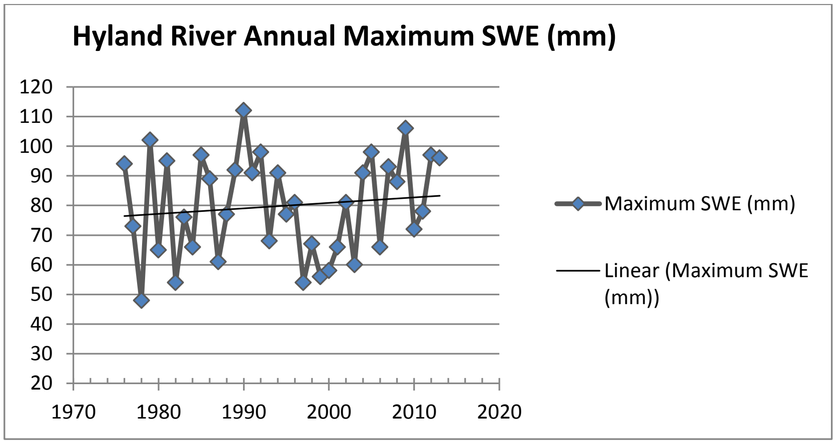


Figure 21a. *Trends in snow water equivalent annual maximum values for the Hyland River station, near the Yukon-NWT border (Yukon Water, Government of Yukon http://yukonwater.ca/).*

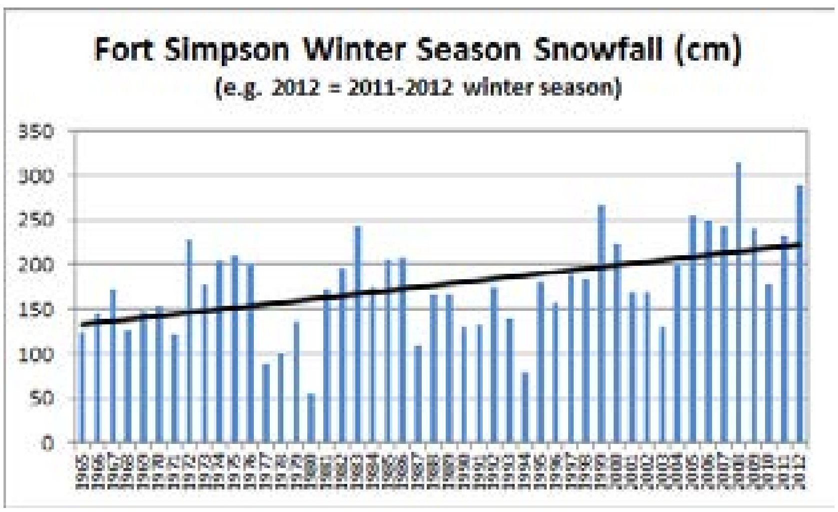
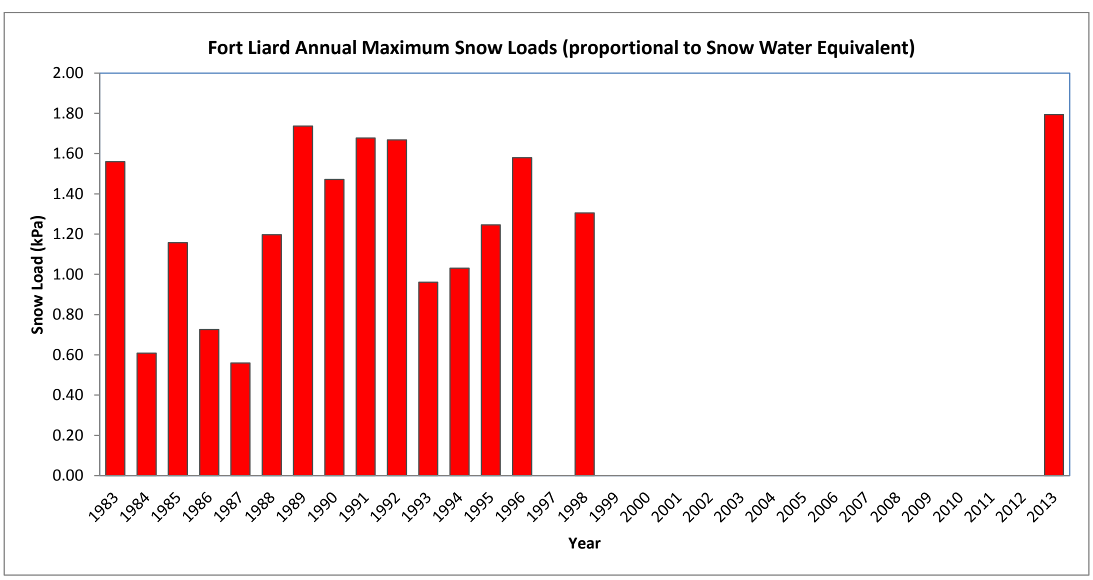


Figure 21b (left). *Trends in Fort Simpson winter snowfall accumulation totals.*

Figure 21c (below). *Fort Liard annual maximum snow loads and snow water equivalents to 2013 indicate higher values in winter 2012-13. No measurements were available for winter 2011-12 (courtesy of AANDC, 2013).*



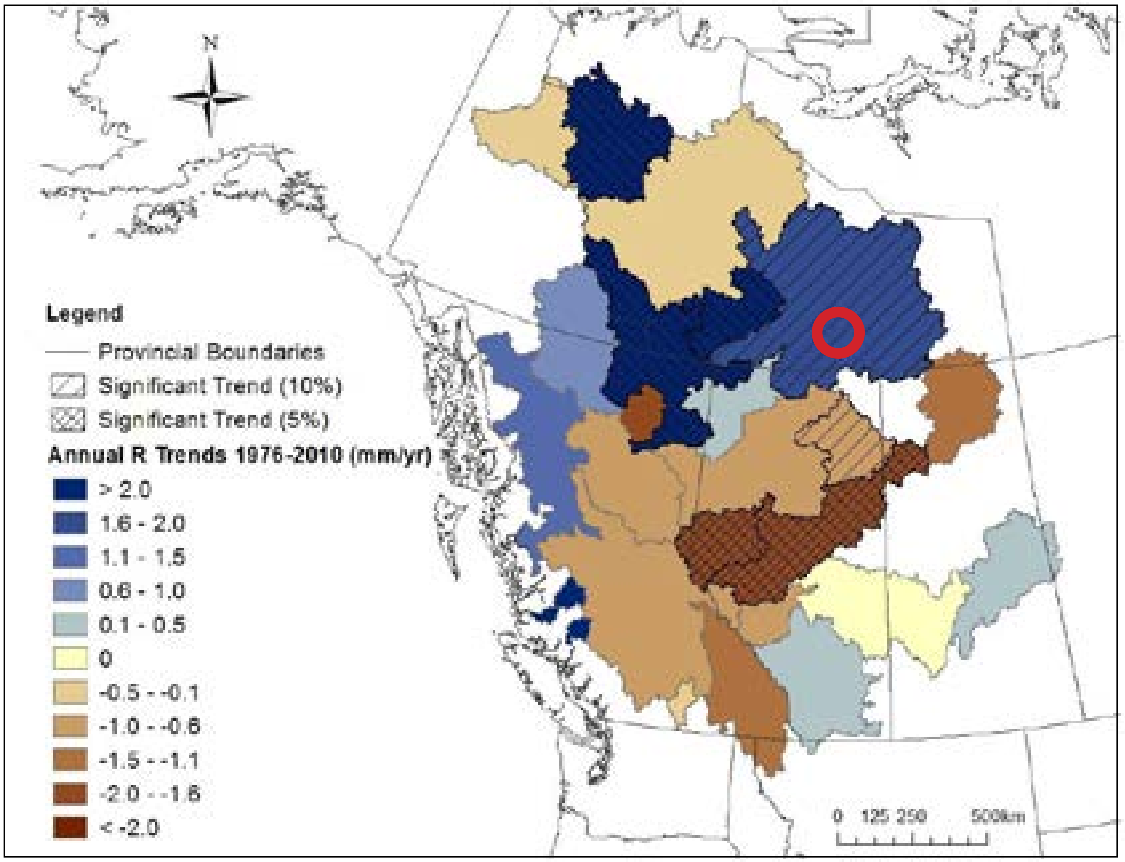


Figure 22. *Map of annual runoff trend slopes for the 1976-2010 analysis period. Basins exhibiting significant trends are illustrated with hatch and line patterns (Bawden, 2013). Study area is delineated with red outline.*

2.5.1. Climate Change Projections and Future Risks

Current climate data and trends demonstrate that the Nahanni Butte region can expect warmer spring temperatures, more rain-on-snow events, heavier rainfalls and some winters with greater extreme snowpack conditions. Furthermore, climate projections suggest that these extreme events may coincide more often in the future. Figure 23 illustrates the projected trends for an ensemble of the IPCC AR5 climate change models (released in late 2013) for the Fort Simpson area, northeast of Nahanni Butte.

The results indicate that the amount and rate of spring warming and precipitation increases that can be expected into the future to the 2080s (2070-2100) are strongly dependent upon the continual rise of accumulated greenhouse gases (GHGs). The future GHG assumptions are captured by the Representative Concentration Pathway (RCP) 4.5 curve indicating moderate decreases in global greenhouse gas emissions, and by the RCP8.5 contour for limited reductions in total GHG emissions into the future. The results are shown for a grid point that includes the Nahanni Range Road. As shown in Figure 23a, for the higher GHG emission assumptions (red curve, RCP8.5), the future warming will be greater and faster; the blue line (RCP4.5) illustrates the warming that is expected under significant GHG emission reductions. In reality, current global GHG emissions are trending closely to the RCP8.5 assumption and dramatic global reductions in GHG emissions would likely be required to reach the RCP4.5 assumption in the future.

Spring is typically defined as including the months of March-April-May; however, for the Nahanni Range Road region, these months represent late winter and currently correspond to the time of maximum snowpack and the start of snowmelt. Figure 23b points to ongoing increases in spring or late-winter total precipitation into the future, whereas Figure 24a indicates the projected percentage increases in annual precipitation compared with the 1981-2010 climate normals. Figures 24b indicates that the greater change from the 1981-2010 climate normals is the increase in the one-day maximum precipitation value rather than the annual mean precipitation, highlighting the potential for more intense rainfall events in the future. When coupled with warming temperatures, it is likely that increased winter precipitation may result in greater snowpacks in some years along with increased frequencies of rain-on-snow events. It is important to note that while some projections show average winter snowpacks in this region decreasing, the trends in the extremes of these snow conditions or snowpacks may increase. Note that trends in extreme precipitation values can differ significantly from trends in average annual precipitation values.

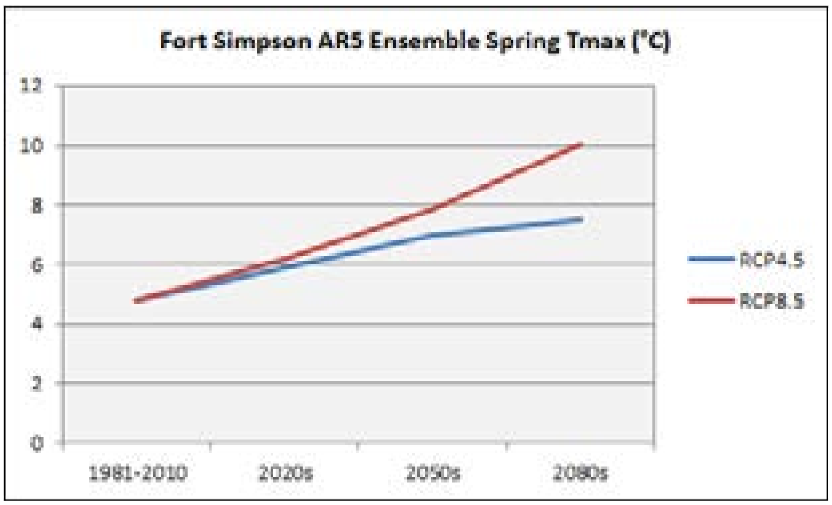


Figure 23a. *IPCC AR5 (IPCC, 2013) ensemble projection of late winter maximum temperatures for the grid cells that include the Nahanni Range Road (from Risk Sciences International).*

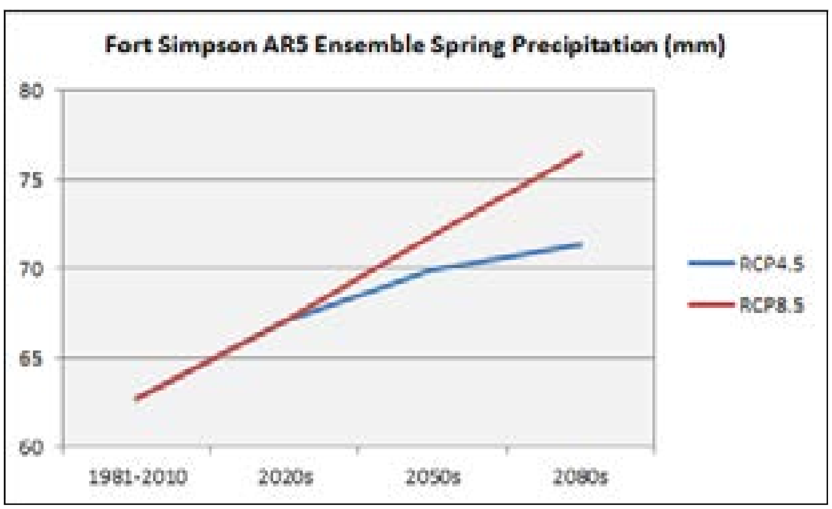


Figure 23b. *IPCC AR5 (IPCC, 2013) ensemble projection of late winter precipitation for the grid cells that include the Nahanni Range Road (from Risk Sciences International).*

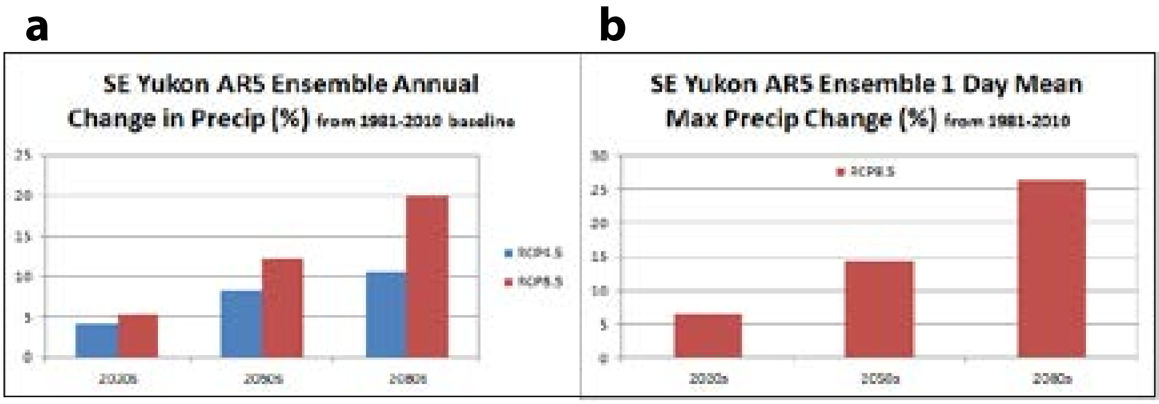


Figure 24. *IPCC AR5 (2013) ensemble (all climate models) projections of **(a)** per cent changes to annual precipitation and **(b)** per cent changes to one-day maximum precipitation compared to 1981-2010 interpolated values (from Risk Sciences International).*

2.6. Adaptation Discussion

The event that flooded Nahanni Butte in the spring of 2012 was the cumulative result of an abnormally heavy snowpack and very warm spring temperatures that coincided with significant rainfall events from June 6-11, 2012. Due to the lack of snow course measurements and limited climate and precipitation data for the region, it was difficult to confirm the severity and return periods of the hydrometeorological conditions, although the runoff and impacts were particularly severe. Greater climate and snow course data coverage would be needed to allow detection of these coincident or 'perfect storm' conditions ahead of time. Ideally, available data could be input into snowmelt and rain-on-snow models tailored for the Northwest Territories to detect potential rapid snowmelt as well as high-risk rain-on-snow conditions. These models could potentially be used to estimate the return period for rain-on-snow events when designing transportation and mining infrastructure. As noted, this forensic analysis was significantly limited in its ability to assess the severity of the climate conditions and their trends due to the lack or shortage of representative snow and rainfall data.

Trends and projections for the future indicate that these types of springtime coincident extremes may continue to increase. Climate change projections also suggest that the likely increases in spring runoff extremes will continue, requiring increased emergency management planning, earlier warnings, consideration of the changes into infrastructure designs, and enhanced reconstruction practices to deal with the impacts on existing communities and vulnerable infrastructure.

The community of Nahanni Butte is concerned that similar flooding events will recur in the near future and has initiated discussions within the community on potential relocation, in spite of the cultural significance of the current location and the potential disruptions to the community. The costs of reducing the flooding risks to the existing community and access road are high, and involve significant and difficult decisions. New or replaced infrastructure and future decisions should be informed by more climate data that show the severity of existing risks, and that include climate projections that indicate the changing/increasing trends with their associated risks. Nahanni Butte and other vulnerable communities in the region would benefit from rain-on-snow monitoring and modelling in order to estimate extreme flood return periods; this type of monitoring may also be useful in detecting and predicting emergency situations.

3. REFERENCES

The above Case Study Events 1 and 2 have been documented in the Climate and Infrastructure Forensic Analysis System (CIFAS), Risk Sciences International and Northern Climate Exchange.

Abdullah, A. and Suleman, M., 2013. Building Bridges - Faster, Better, Safer Under Emergency Conditions. Paper prepared for presentation at Structures-Bridges Sessions of the 2013 Conference of the Transportation Association of Canada, Winnipeg, Manitoba, Yukon Highways and Public Works, 12 p.

Aboriginal Affairs and Northern Development Canada (AANDC), 2013. Snow Surveys. Accessed December 21, 2013, http://www.aadnc-aandc.gc.ca/eng/1100100027479/1100100027483.

Bawden, A., 2013. Recent changes in patterns of western Canadian river flow and association with climatic drivers: A CROCWR component. Thesis in fulfillment for the degree of Master of Applied Science in Civil and Environmental Engineering, Waterloo University, 2012. Accessed December 14, 2013, https://uwspace.uwaterloo.ca/handle/10012/8075.

CBC, June 11, 2012a. Flooding creates weekend mayhem in Yukon and NWT: Residents of several communities in Yukon, BC and NWT moved as a precaution. Accessed December 13, 2013, http://www.cbc.ca/news/canada/north/flooding-creates-weekend-mayhem-in-yukon-and-n-w-t-1.1146695.

CBC, June 14, 2012b. CanTung mine rations fuel due to road closure Nahanni Range: Road remains closed due to three washouts. Accessed December 13, 2013, http://www.cbc.ca/m/touch/canada/north/story/1.1291980.

CBC, June 19, 2012c. 100 miners out of work due to Yukon road closure: Nahanni Range Road to North American Tungsten mine washed out in 3 spots. Accessed Dec 14, 2013, http://www.cbc.ca/news/canada/north/100-miners-out-of-work-due-to-yukon-road-closure-1.1279892.

CBC, October 23, 2012d. Nahanni Butte, N.W.T., still without fixed access road: Road has been under water since summer flooding. Accessed December 13, 2013, http://www.cbc.ca/news/canada/north/nahanni-butte-n-w-t-still-without-fixed-access-road-1.1265609.

Government of the Northwest Territories, June 15, 2012. GNWT Emergency Bulletin: Liard River. Accessed December 13, 2013, http://news.exec.gov.nt.ca/gnwt-emergency-bulletin-liard-river-june-15-5pm/.

Environment Canada, 2013a. Water Survey of Canada: Hydrometric Data. Accessed December 13, 2013, http://www.wsc.ec.gc.ca/applications/H2O/index-eng.cfm.

Environment Canada, 2013b. Meteorological Service of Canada: Historical Climate Data. Accessed February 12, 2014, http://climate.weather.gc.ca/.

Environment Yukon, 2013. Snow Survey and Water Supply Forecast. Access date, http://www.env.gov.yk.ca/air-water-waste/snow_survey.php.

Gauthier, M.-E., Leroux, D. and Assani, A., 2008. Vulnerability of culvert to flooding. Proceedings, 28th Annual Esri International User Conference, San Diego, CA, August 4-8, 2008.

Government of Yukon, 2013. Yukon Water. Access date, http://yukonwater.ca/monitoring-yukon-water/water-data-catalogue.

Northern News Service, June 18, 2012a. Floodwaters remain in Nahanni Butte. Accessed December 13, 2013, http://www.nnsl.com/frames/newspapers/2012-06/jun18_12nah.html.

Northern News Service, June 28, 2012b. Nahanni Butte cleans up: Residents might be allowed home this week. Accessed December 13, 2013, http://www.nnsl.com/frames/newspapers/2012-06/jun28_12NAH.html.

Northern News Service, August 15, 2012c. Nahanni Butte airs frustrations over flood response: Government officials promise more assistance. Accessed December 13, 2013, http://www.nnsl.com/frames/newspapers/2012-08/aug15_12nah.html.