Considerations for Addressing Climate Change Adaptation for Transportation Infrastructure in Highway Management, Design, Operation and Maintenance in British Columbia

Best Practices Document

B.C. Ministry of Transportation and Infrastructure
Nodelcorp Consulting Inc.
Pacific Climate Impacts Consortium

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1 Introduction

Disruption to transportation systems can be costly to society in terms of interruption of access to emergency, medical and educational services, delays in delivery of goods and services and lost productivity. As climatic conditions change there is potential for increased disruption to transportation systems especially from extreme weather events. Understanding risks and impacts to transportation from climate changes and developing design and maintenance responses over the service life of infrastructure can promote and enhance highway reliability.

The BC Ministry of Transportation and Infrastructure (BCMoTI) has engaged in a number of projects to consider vulnerability risk to transportation infrastructure in BC from future changes in climate. The intent is to understand potential risks to the transportation system and develop adaptation measures to address potential issues. This Best Practices Document has resulted from findings, knowledge and experience acquired from conducting these projects and reviewing others.

This Best Practices Document provides guidance on integrating climate change considerations into ongoing management, planning, engineering, maintenance and operations activities within the British Columbia Ministry of Transportation and Infrastructure (BCMoTI). It outlines general approaches to consider for adapting practices to accommodate impacts of changing climate on B.C. highway infrastructure systems. The general guidance provided in this document could be modified and integrated into operating practices, procedures, and technical circulars and scoping documents.

This project benefited from partnering with Natural Resources Canada (NRCan) under their Adaptation Platform intended to advance adaptation to climate change in Canada. BCMoTI has contributed to the NRCan Coastal Management theme and this initiative has supported the development of this Best Practices Document.

2 Best Practice Development Process

The development of the best practices outlined in this document followed from a process of infrastructure and climate risk assessments with findings and synthesis and analysis of these and other work that was conducted over the period 2007 through 2014. Throughout this process BCMoTI engineering expertise included structural, hydrotechnical, geotechnical, geometric design, traffic as well as environmental personnel. External specialists were involved from areas including transportation infrastructure, engineering risk assessment, hydrology, meteorology and climate science. These personnel provided input and information in various forms including participation in risk-workshops, data, modelling and output, report production, and document review. These experts subjected the assumptions, data and findings to professional scrutiny.

For the purposes of this work, we included analysis of five highway infrastructure risk assessments conducted by BCMoTI and 20 risk assessments of infrastructure systems from across Canada conducted under the auspices of the Engineers Canada PIEVC initiative. Each study included in the analysis was conducted with input and guidance from expert working groups, who ensured that the assessments were conducted in accordance with the PIEVC Engineering Vulnerability Assessment Protocol and applying the most robust and scientifically defensible climate data and engineering analysis.

In total, we reviewed and synthesized the findings from the 25 case studies to identify common issues across all Canadian infrastructure systems, within the limitations of the data available at the time of the review. In total, we reviewed our work with 79 internal BCMoTI experts and external specialists. The outcomes from this synthesis and review were used to develop the best practices outlined in this document.

A schematic roadmap of the Best Practices Development Process is presented in **Figure 2.1**. The roadmap demonstrates that the process was subjected to engineering and climate science peer review from start to finish. Additionally, the development process was based on a logical sequence of assessment, review, syntheses and validation over a period of four years. Based on this process, we believe that the best practices outlined in this document represent a robust and pragmatic approach to addressing climate change issues within transportation systems.

In **Table 2.1**, we present BCMoTI experts that participated in reviewing the best practices outlined in this guidance document.

In **Table 2.2** we present the types of expertise (and number of personnel from each field) that were assembled for the BCMoTI risk assessment projects, which have formed the basis for this best practices document.

Figure 2.1: Best Practice Development Road Map

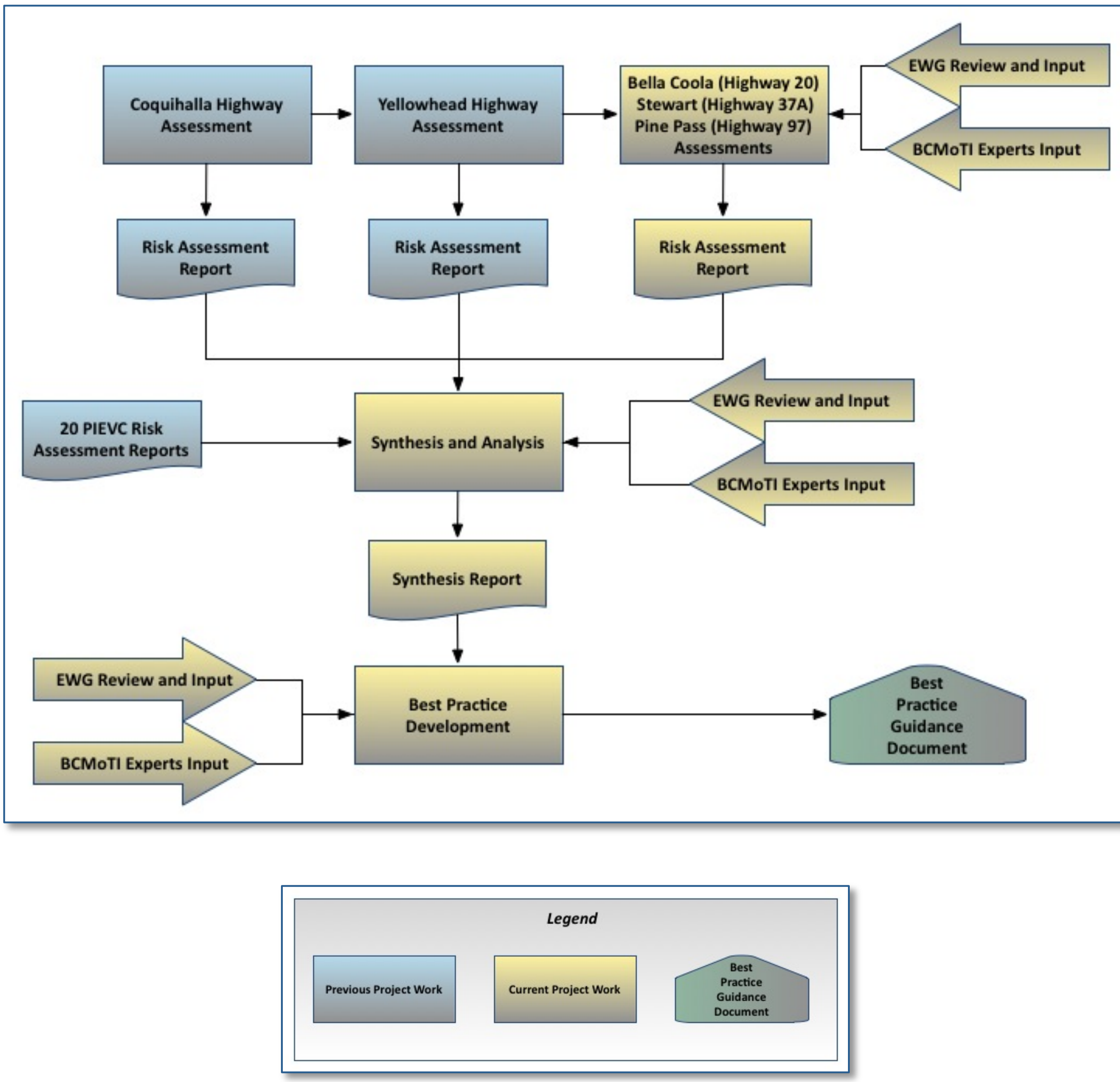


Table 2.1: Contributions and Review for Best Practices

Expertise	Organization
Chief Engineer	BCMoTI
Directors & Managers	BCMoTI
Structural Engineering	BCMoTI
Geotechnical Engineering	BCMoTI
Hydrotechnical Engineering	BCMoTI, KWL
Climate Change Infrastructure Vulnerability	Nodelcorp
Hydrology	NHC
Climate	BCMoTI
Environmental	BC Min of Environment

Table 2.2: Contributors to BCMoTI Risk Assessments

Expertise	Personnel	Organization
Chief Engineers	2	BCMoTI, Min Transportation NL
Directors & Managers	13	BCMoTI, Transport Canada
Climate Change Infrastructure Vulnerability	4	Engineers Canada, Stantec, Nodelcorp
Environmental	7	BCMoTI, BC Min Environment, Min Transportation NL
Transportation Engineers	3	Transport Canada, Ontario Min Trans
Structural Engineers	7	BCMoTI,
Geotechnical Engineers	8	BCMoTI
Geometric & Traffic Engineers	3	BCMoTI
Hydrotechnical Engineers	4	BCMoTI
Hydrologists	3	NHC, KWL
Avalanche	3	BCMoTI
Design & Survey	3	BCMoTI
Operations & Maintenance	6	BCMoTI
Technicians	3	BCMoTI, PCIC
Climate Scientists	6	PCIC, NHC
Meteorologists	2	Environment Canada
Project Management	2	BCMoTI

Total	79

3 Background

BCMoTI has established a basis for this Best Practices Document from conducting climate change vulnerability risk assessments for existing infrastructure on five B.C. highway segments that included:

- Coquihalla Highway between Hope to Merritt
- Yellowhead Highway 16 between Vanderhoof and Priestly Hill
- Highway 20 in the Bella Coola Region
- Highway 37A in the Stewart (Bear Pass) Region
- Highway 97 in the Pine Pass Region

The Engineers Canada, Public Infrastructure Engineering Vulnerability Committee (PIEVC) Engineering Protocol for Infrastructure Vulnerability Assessment and Adaptation to a Changing Climate (Protocol) was used as a basis for these vulnerability risk assessments.

The five highway segments evaluated in these assessments covered a diverse range of climatic and geographical conditions throughout British Columbia.

For the purposes of these assessments, engineering vulnerability risk to climate change is defined as the shortfall in the ability of public infrastructure to absorb the negative effects, and benefit from the positive effects, of changes in the climate conditions used to design and operate infrastructure. Vulnerability is a function of:

- Character, magnitude and rate of change in the climatic conditions to which infrastructure is predicted to be exposed
- Sensitivities of infrastructure to the changes, in terms of positive or negative consequences of changes in applicable climatic conditions
- Built-in capacity of infrastructure to absorb any net negative consequences from the predicted changes in climatic conditions

Engineering vulnerability risk assessment requires assessment of all three elements.

The five highway segments that have been evaluated comprise a grid that covers the major portions of the B.C. Highway System covering the typical range of geographic and climatic conditions that BCMoTI may encounter in the operation of that system. We draw upon recommendations and conclusions from this body of work to inform the development of this Best Practices Document.

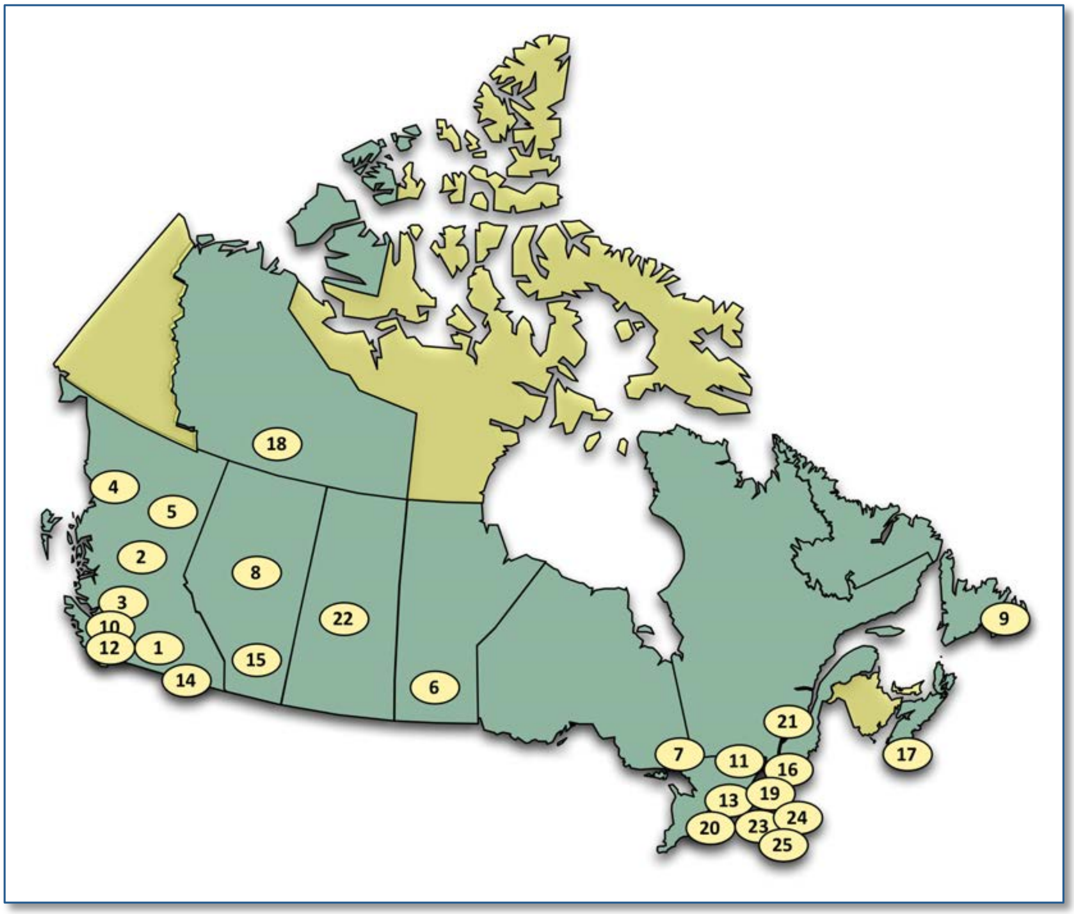
To support this development we reviewed 20 other vulnerability risk assessments conducted using the Public Infrastructure Vulnerability Committee (PIEVC) Protocol across Canada. This synthesis provides a basis for expanding the best practices outlined in this document to other regions and jurisdictions across Canada. In total, 25 vulnerability risk assessments were considered, as outlined in **Table 3.1**.

Table 3.1 - PIEVC Infrastructure Vulnerability Risk Assessments Considered in the Synthesis Review

#	Date	Owner	Region	Infrastructure
1	Jun 2010	BCMoTI	BC	Coquihalla Highway (B.C. Highway 5) between Nicolum River and Dry Gulch
2	Apr 2011	BCMoTI	BC	Yellowhead Highway 16 between Vanderhoof and Priestly Hill
3	Sep 2013	BCMoTI	BC	Highway 20 in the Bella Coola Region
4	Sep 2013	BCMoTI	BC	Highway 37A in the Stewart Region
5	Sep 2013	BCMoTI	BC	Highway 97 in the Pine Pass Region
6	Nov 2007	Portage la Prairie	MB	Water Resources Infrastructure
7	Mar 2008	City of Greater Sudbury	ON	Roads
8	Mar 2008	City of Edmonton	AB	Quesnell Bridge
9	Mar 2008	Town of Placentia	NL	Water Resources Infrastructure
10	Apr 2008	Metro Vancouver	BC	Metro Vancouver Sewerage Area
11	Apr 2008	Government of Canada	ON	Buildings
12	Dec 2009	Metro Vancouver	BC	Fraser Sewerage Area
13	Jun 2010	Toronto Regional Conservation Authority	ON	Flood Control Dams
14	Oct 2010	City of Castlegar	BC	Stormwater Systems
15	May 2011	City of Calgary	AB	Water Supply and Treatment
16	Jun 2011	Town of Prescott	ON	Sanitary Sewage
17	Aug 2011	City of Shelburne	NS	Sewage Treatment
18	Oct 2011	Government of the Northwest Territories	NT	Highway 3
19	Dec 2011	City of Toronto	ON	Culverts
20	Feb 2012	City of Welland	ON	Stormwater - Wastewater
21	Mar 2012	Trois Rivieres	QC	Drainage
22	Mar 2012	University of Saskatchewan	SK	Buildings
23	Jun 2012	Infrastructure Ontario	ON	Buildings
24	Sep 2012	Toronto Community Housing Authority	ON	Buildings
25	Sep 2012	Toronto Hydro	ON	Electricity Distribution

The geographic coverage of these assessments is outlined in **Figure 3.1**. The assessments covered most of the provinces and territories of Canada. Only Prince Edward Island, New Brunswick, Yukon and Nunavut are not currently represented in this analysis. We understand that several of these jurisdictions will be hosting PIEVC vulnerability risk assessment work.

Figure 3.1 – Map of Vulnerability Risk Assessment Locations



	Jurisdictions where PIEVC vulnerability risk assessments **HAVE** been conducted
	Jurisdictions where PIEVC vulnerability risk assessments **HAVE NOT** been conducted

4 Context

This document contains information that can be used by infrastructure owners and engineering professionals to incorporate considerations of changing climate conditions into the design, construction, operation, maintenance, and management of water handling infrastructure systems including drainage, and specifically road infrastructure systems. This guidance will provide a firm basis for the development of tools such as operating practices, procedures, technical circulars and scoping documents.

5 Limitations

While we are confident that this document provides a reasonable high-level assessment of common risk drivers, we note the following limitations:

1. Twenty-five assessment reports, covering a range of infrastructure types, do not represent a robust sample that would allow statistically significant analysis.

2. This document does not contemplate potential emerging risk patterns associated with other infrastructure components or climate drivers. The reader should not conclude that drainage issues are the only common risk drivers across Canada's infrastructure systems. Other common risk drivers may exist but were not within the scope of the current work.

3. This document was developed based on PIEVC vulnerability risk assessments conducted over the five-year period 2007 through 2012. The document does not contemplate the updated AR5 climate change projections identified in the most recent IPCC report.

6 Overarching Considerations

6.1 Vulnerability to High Intensity Precipitation Events was Identified in Every Assessment

Without exception, every vulnerability risk assessment that we reviewed identified high intensity precipitation events as risk factors affecting infrastructure systems designed to manage water flow. Where the assessments directly looked at drainage systems, these factors were generally deemed to be risk drivers. Even where assessments did not identify these events as high risk, they were often identified as coincident or related risks associated with other factors that were deemed to drive the infrastructure's risk profile.

6.2 Vulnerability to High Intensity Precipitation Events is Common Across Canada

These impacts were observed in every region we considered. The meteorological drivers for the events may vary, but the vulnerabilities are consistently observed. For coastal BC the primary driver of these events was typically identified as atmospheric river type events known as Pineapple Express. Inland, the driver may be attributed to convection storms, while the Atlantic region would typically attribute them to tropical storm or hurricane events.

Without exception, the future climate projections prepared for the vulnerability risk assessments projected increases in frequency and duration of high intensity precipitation events.

6.3 The Need for Relevant Climate, Stream Flow Data and Modeling Information

There is clearly a need for high-quality, locally relevant, lengthy and continuous climate information, stream flow data and future climate modeling projections.

It is of upmost importance to maintain and indeed increase the collection of weather station data and stream flow data (river gauge data), as these are critical inputs to any analysis regarding climate change impacts and adaptation. It is also especially important to collect station data from locations at elevation in BC as there are many mountainous regions in the province; as currently many current stations (Environment Canada) are found in valleys and generally at lower elevations like airports.

Engineering has traditionally relied on past weather data for design work. Currently many historical weather records in BC are available for short periods such as 30 years. However, for engineering design, longer and continuous data records are more relevant. As engineering is often concerned with designing for extreme events (such as flood levels) of 50, 100 and 200 years, the availability of longer data sequences for analysis of return periods of extreme events is essential.

In order to project climate conditions that infrastructure may experience during their lifespan, lengthy and sequential climate records are of immense importance in climate modeling. Lengthy historical data is preferred as a smaller culvert's design lifespan may be 50 years and bridges and larger culverts may last 75-100 years; thus it helps having longer data records when modeling and designing for extreme events infrastructure may experience. As infrastructure is designed and built throughout BC, and as climate and drainage basins vary considerably in their characteristics per location, more comprehensive climate and stream flow data is required.

It is important to use the most current climate information in engineering, operation and maintenance activities to reflect ongoing changes in climate, for example, using current IDF curves for designing drainage systems. We also observed that it is important not to overlook or underestimate the impact of unique local weather phenomena and terrain. Relying solely on meteorological data and climate forecast information, can underestimate synoptic analysis that is informed through local knowledge.

Climate projections are much more robust when based on most recent models and larger ensembles of global and regional climate model runs. Climate projections used in earlier PIEVC case studies relied on smaller numbers of global and regional climate model runs based on a smaller number of greenhouse gas emission scenarios. This increased the level of uncertainty associated with vulnerability risk assessment outcomes. However, this suggests that obtaining robust climate projections for any one particular project could be expensive, and this could present a significant barrier to organizations contemplating vulnerability risk assessment work.

Given these circumstances, it is necessary and indeed critical to provide and maintain central repositories of robust, locally relevant, lengthy and sequential climate data and modelling information. Fortunately in BC, The Pacific Climate Impacts Consortium (PCIC) is developing and making available significant climate information for climate change projects. This is discussed further in **Section 6.3**.

6.4 Combinations are Important

Our review highlighted that the risks associated with high intensity precipitation events could be significantly exacerbated by sequences of events or events occurring in combination regarding climate and terrain.

We noted that high intensity precipitation events might be accompanied by high winds and hail. This is especially the case when the mechanism driving the event is convection. The combination of high intensity rainfall, wind and hail can exacerbate drainage issues. Wind creates more debris and hail can clog drainage systems.

Other effects, such as debris flow and slope failure contributing to drainage system vulnerabilities, were a recurring theme across many of the studies we reviewed. Sometimes, the studies evaluated this matter in detail while in other cases it was raised as a subjective qualifier of risk exposure estimates. In any case, there is an emerging theme of debris compromising drainage infrastructure capacity leading to increased vulnerability to precipitation events.

Our review also indicated that seemingly unrelated issues might exacerbate the risks associated with these events. For example, Mountain Pine Beetle infestation will kill forest cover causing an increase in debris flow and can reduce the permeability of the terrain surrounding drainage systems. These combinations significantly increase the risk of drainage system failures during intense precipitation events. Debris clogging will reduce the capacity of the drainage system while reduced permeability would tend to increase the volumes of water received at those systems.

We noted that there are occasions where combinations or sequences could potentially provide opportunities to reduce risks. For example, in some studies drought was identified as a high-risk issue and intense precipitation events were also identified as risk factors. In these situations, infrastructure owners have opportunities to inspect, maintain, repair or upgrade drainage systems during dry periods so that the infrastructure would be better equipped to deal with the intense precipitation event when it ultimately occurs. Thus, organizations that have a good handle on evolving climate change can use climate variability as one way to manage adaptation work so that the organization is prepared when extreme events eventually occur. The organization does not interpret the drought, for example, to be permanent but rather as a quiet period between other extreme events.

7 Best Practices

Based on the work conducted by BCMoTI and the greater body of PIEVC work conducted under the auspices of Engineers Canada, we have developed sixteen best practices that may be considered in the development of operating practices, procedures, and technical circulars and scoping documents. Each best practice is supported with:

- A brief explanation of its context and broader interpretation; and
- A synopsis of how the best practice may be implemented.

Best practices should not be interpreted as mandatory requirements. Rather, they outline a set of actions that BCMoTI may wish to incorporate into its management and operations to address evolving climate change concerns. A particular best practice may not be applicable in all circumstances. However, the overall range of issues covered by the best practices establishes a methodology to ensure that climate change considerations are embedded within the organizational culture.

While the primary focus of the current work was intense precipitation events, we have noted that much of the approach outlined within this set of best practices is more generally applicable to addressing the broader impacts of climate change within the organization. This is a reasonable outcome from this analysis. Adaptive responses to high intensity precipitation events can be categorized into a set of typical professional, engineering, management, maintenance and operational practices. While these practices do address the immediate issue of intense precipitation impacts on B.C.'s highways, they can also generally be applied to a much broader range of climate change issues.

The sixteen best practices are outlined in **Table 7.1**.

Table 7.1 Best Practices

7.1 Data

7.1.1 Use Up to Date Weather and Climate Data

a) Interpretation

In our review of PIEVC vulnerability risk assessments from across Canada we noted that some jurisdictions might still be using very dated climate information in their ongoing engineering, operation and maintenance activities. In some cases municipalities and others may be using IDF curves based on meteorological data from dated sources as a basis for designing drainage infrastructure and this may in fact be typical. As well, some codes and standards may contain meteorological information from the 1970s.

Clearly, when climate is changing, engineering, operation and maintenance practices based on out-of-date meteorological information may be compromised. Not all older weather data is out-of-date, but older vintage data should be challenged and, where necessary, updated or replaced with more relevant data.

b) Application

- Review the climate data embedded within ongoing management, engineering, operation and maintenance. Within the review evaluate the vintage of the data and compare how the data set calibrates with climatic conditions observed over the last decade
    - Reviews should be conducted on a routine basis, annually or on a frequency deemed sufficient to identify relevant changes in the data set
- As appropriate, revise and update weather information, IDF curves and other meteorological-based tools that are found to be deficient in the review

- Record results from these reviews and updates in the database or filing system established to address **Best Practice 7.1.2.**

7.1.2 Establish Extreme Climate Event Monitoring Programs

a) Interpretation

B.C. highway systems have experienced significant service interruptions caused by high intensity precipitation events. We found that failure reports and engineering analysis of those events significantly helped inform the assessment of climate change risk profiles throughout the B.C. highway system. Highway and drainage infrastructure systems in different locations and regions often utilize similar design elements, construction materials and techniques, and experience comparable weather phenomena.

BCMoTI should continue to monitor the impact of high intensity precipitation events on BC's highway infrastructure and maintain records of these events. In particular, it is important that failure reports, weather data and technical analyses be generally available so that the lessons from one failure can be more generally applied across the highway system, as appropriate.

b) Application

- Set up a documentation system or database for highway failure flooding events that occur across the highway system. Maintain records of:

    - Technical findings
    - Photos of relevant features of the infrastructure failure
    - Meteorological conditions that led up to the failure
    - Operations and maintenance activities to return the highway to normal operation
    - Changes in regional practice arising from the incident

- As appropriate, draw upon the database to inform new design or refurbishment activities across the highway system

- As appropriate, draw upon the database to inform the broader technical community through organizations such as the Transportation Association of Canada

7.1.3 Include Extreme Precipitation Events in Risk Analysis

c) Interpretation

Every climate change vulnerability risk assessment that we reviewed identified high intensity precipitation events as risk factors affecting infrastructure systems designed to manage water flow. Where the risk assessments directly evaluated drainage systems, these factors were generally deemed significant risk drivers. Where risk assessments did not identify high intensity precipitation events as high risk, they were often identified as coincident or related risks associated with other factors that drove the infrastructure's risk profile.

The review considered 8 of 11 provincial and territorial jurisdictions in Canada. These impacts were observed in every region considered.

The meteorological drivers for the high intensity precipitation events may vary, but the vulnerabilities are consistently observed. For coastal BC the primary driver of high intensity precipitation events was typically identified as Pineapple Express atmospheric river type events. Inland, the driver may be attributed to convection storms, while the Atlantic region would typically attribute them to tropical storm or hurricane events.

Without exception, the climate projections prepared for the vulnerability risk assessments projected increases in frequency and duration of high intensity precipitation events.

d) Application

- High intensity precipitation events should be considered in every risk assessment of infrastructure vulnerability and should be included in the list of climate parameters
    - This mandate should be outlined in all relevant procedures and technical guidance documents developed by BCMoTI
    - Where a BCMoTI staff member or contractor determines that high intensity precipitation events are not relevant to a particular situation, they should document and justify this decision

7.1.4 Consider Combinations and Sequences of Events

a) Interpretation

The five BCMoTI vulnerability risk assessments identified that combinations of events can significantly exacerbate the impact of high intensity precipitation events. In our review of

PIEVC vulnerability risk assessments, we found that infrastructure systems across Canada all exhibit similar sensitivities to combinations and sequences of events.

External factors can compromise the design, assessment, operation or maintenance of drainage systems. Accumulations of debris in ditches and within culverts can significantly reduce the capacity of these drainage systems, affecting their ability to absorb and manage high intensity precipitation events. External factors such as land clearing, forestry activities, and Mountain Pine Beetle infestations can also contribute to debris flows that tax drainage systems.

Combinations of weather events can also compromise the ability of infrastructure systems to accommodate intense precipitation events. For example, prolonged periods of rain may saturate soil and reduce the permeability of the natural ecosystem, leading to increased overland flow during subsequent high intensity precipitation events. Prolonged periods of drought affecting the permeability of the soil can have the same effect, increasing overland flows with heavy precipitation. Also, heavy runoff (freshet) conditions because of above average snowpack, in some years, combined with high melting from warm conditions and high intensity precipitation events can be problematic.

Based on these findings, simply relying on IDF curves may not be sufficient. It is also important to take into account factors such as debris flow, hail, or changes in physical nature of the watershed that feeds the system. These contributing factors can overwhelm drainage appliances that have been sized on IDF curve information only.

b) Application

- Within training programs, procedures and technical bulletins ensure that staff and contractors are apprised of the need to consider and address external factors such as land clearing, forestry and Mountain Pine Beetle infestations when sizing drainage systems.

- In developing climate change projections, ensure that that staff and contractors are apprised of the need to consider combinations of weather events that could contribute to overcharging drainage systems. These may include, but are not limited to:

    - Rain on frozen ground
    - Rain following periods of drought
    - Intense rain following a prolonged period of moderate precipitation
    - Heavy snowfall followed by warm periods and intense precipitation leading to high freshet flows
    - Intense rain events combined with hail

7.1.5 Use Relevant and Robust Climate Change Information

a) Interpretation

In order to effectively address climate change, staff should have access to reliable, robust and regionally relevant climate change projection information. They should base their technical analysis and decision-making on the highest quality information available within the context of their budgets.

For a stand-alone project, developing climate change information can be very expensive and could potentially consume a large portion of project budgets. Fortunately, organizations such as PCIC are creating repositories for this type of information. Infrastructure staff and contractors should work with the information contained in these repositories and develop familiarity with the way climate change information is presented.

It is also important that infrastructure staff and contractors match the complexity and precision of the climate data with the actual requirements of the project. It can be tempting to pursue very detailed or very complex climate change data sets when general values may suffice. Conversely, it can be tempting to apply very general, high-level, information in situations where more robust data may be required, either out of lack of familiarity or to avoid expenditures for higher quality data.

Historically Environment Canada used manual processes to review and maintain weather data, however, recently they have automated this process. Unfortunately, an automated process may expunge outlier weather data. While many of these outliers are invalid data, some of them are legitimate extreme events that are relevant to engineering practice and design. As a result, users of weather data must ensure that they have a solid understanding of how the data has been managed and if there is a possibility that relevant data may have been expunged from the database. This may require input from a regional climate or meteorological specialist. These specialists should be conversant with the data collection methodology for databases and the assumptions on how extreme values are treated, included or excluded by automation rules.

Where complex, detailed or very precise data is needed it may be necessary to have site-specific projections developed. However, for many activities, generalized information available from Provincial, Federal or other (such as PCIC) databases may suffice.

It is important that staff and contractors:

- Be aware of where and how to access the climate information;
- Have sufficient training in the use of such information to use it effectively; and
- Seek advice from climate change professionals when data analysis demands exceed their training and experience.

b) Application

- Identify sources of robust climate change information that BCMoTI staff can access to support ongoing activities.

    - Within internal standards and procedures define expectations and relevant parameters that apply to specific Ministry applications

- Monitor advisory documentation and guidance provided by professional associations, regulators and standards groups. For example, APEGBC recently suggested a 10% increase in design discharge values (when using stream flow magnitude-frequency relations and a statistical trend is not detectable) and a 20% increase in flood magnitude values (in small basins where information on local conditions is inadequate and a statistically significant trend is detected).

    - Ensure that design safety factors provided by these groups are incorporated, as appropriate, into design and engineering standards used by the organization
    - Review guidance for relevance
    - Document guidance documents considerations and outcomes
    - Ensure that recommendations arising from review of guidance documents are incorporated in relevant design and operational documents throughout the organization

- Establish training programs to ensure that staff knows how to access and apply climate change information. Training should emphasize:

    - Where to get information
    - The level of precision and formats required to support routine activities
    - When and where to seek support from internal and external climate change specialists

7.1.6 Use Climate Projections Based on Ensembles of Climate Models

a) Interpretation

Climate projections uncertainty can be identified and potentially narrowed when based on larger ensembles of climate models.

Climate change projections are based on very sophisticated modeling and analysis derived from socioeconomic and greenhouse gas emission forecasts. A large number of models are used in developing climate projections and the models all have different strengths and weaknesses. Due to the inherent uncertainty associated with modeling, current practice is to apply an ensemble approach where more than one model is used to establish the boundaries of projected climate change.

The underlying emission forecasts and socioeconomic assumptions that feed into climate models often are not stated when presenting climate change projection information. While these factors introduce some uncertainty into climate projections, the uncertainty can be managed through appropriate data treatment and climate scenario development. These practices are typically outside of the experience of staff responsible for infrastructure. It is therefore important that staff consult with climate professionals to ensure that they understand the overall integrity and limitations of the information they are planning to use and incorporate appropriate measures from their own professional discipline to accommodate these factors within their work.

b) Application

- Ensure that internal climate change information is based on ensembles of climate projections
    - Consult with climate change specialists to ensure that the models included within the ensembles best represent the data requirements for the particular application
- Within the training programs outlined in **Best Practice 6.1.5**, ensure that staff are made aware of the need to ask for and apply ensemble climate projection information

7.2 Personnel

7.2.1 Apply Quantitative Data and/or Professional Judgement when Appropriate

a) Interpretation

There is a common misconception that risk review processes based on computational approaches are more robust and reliable than other, judgment-based, methodologies.

Quantitative climate change vulnerability risk assessment methodologies to establish probability and severity of weather events effects on infrastructure nonetheless require the application of professional judgment in establishing the numerical factors/parameters to include in the calculations. Professional judgment is buried within a numerical milieu. The process generally requires more analysis that may seem obscure to non-engineers.

The added value of quantitative approaches is that the engineers on the team may be more comfortable with this way of applying professional judgment. The weakness is that quantitative approaches can often be interpreted to be more rigorous than other methodologies. There are very few situations where there is sufficient data to avoid professional judgment. It is highly unlikely that the team will have sufficient data for future conditions to draw conclusions based completely on computations.

Climate change vulnerability risk assessment activities that rely solely on analytical methods for assessing probability of events and severity of impacts can underestimate or overestimate overall risk in some cases. Circumstances that have not been observed or numerically recorded may not be included; therefore, what has not been historically observed may not be considered as a potential risk. The essence of risk management is the identification of hazardous conditions ***before*** they actually occur in order to mitigate the impacts of those hazards. This can cause a dilemma, as events that may cause failures could be the same events for which teams may have no measured data upon which to base numerical analysis.

Conversely, climate change assessment work based solely on professional judgment might overlook projected data, and/or robust historical data. Where available, high-quality projected data, measured data and observations should always be used in vulnerability risk assessment work. This information can significantly affect the overall evaluation of climate change risk. For example, on a theoretical basis a particular weather event might be deemed to be very risky, while in practice such events have had minimal impact on the infrastructure.

This could be the result of over-design not contemplated in the analysis or routine operation and maintenance practices that mitigate the risk. Without this information, it is possible to overestimate risk profiles and institute unnecessary risk mitigation activities.

It is important that vulnerability risk assessments strive for a balance between strictly analytical or strictly judgment-based processes. Professional judgment can provide greater insight into the implications of quantified risks and analysis can provide assurance that professional judgment is based on real hazards.

b) Application

- Where available, climate change assessment work should incorporate measured historical data and observations

- When robust information is not available, work should advance on the basis of the best professional judgment of ***teams*** of staff, professionals, climate specialists and contractors, as appropriate

- When interdisciplinary teams identify that data gaps preclude advancing the work; additional study, analysis and research should be conducted to develop information sufficient to support the work

7.2.2 Assign Staff to Monitor and Manage Climate Change Issues Related to Transportation Engineering

a) Interpretation

Maintaining a current awareness of climate change issues could potentially consume considerable staff resources and time. While it is important for all key staff and contractors to have a passing awareness of the potential impact of climate change on their ongoing activities, it is not necessary that everyone have a detailed and specialized understanding of these issues.

Staff and contractors should be able to access relevant climate change information and advice from internal resources. Detailed training and resource support with respect to climate change issues can be focused on these internal resources that can disseminate appropriate guidance and information within the organization, as necessary.

This approach maintains better overall budgetary control while ensuring that critical climate information is used to inform Ministerial activities.

The number and location of these internal experts will depend on geographic access requirements and the need to ensure that the experts can attend meetings as necessary throughout the Province. However, as a starting point, BCMoTI should consider designating one centrally located resource that can provide climate change services throughout the Ministry, as appropriate.

b) Application

- Establish a, centrally located, internal climate change information coordination function to work with project teams across the Ministry and others, as appropriate
    - This function can be integrated within an existing position to provide information and contacts for climate change information
- As the demand for climate change expertise evolves across the Ministry, establish similar responsibilities in other positions across the Ministry

7.2.3 Establish Multidisciplinary Climate Change and Engineering Adaptation Review Teams

a) Interpretation

BCMoTI staff should work with climate and meteorological and hydrotechnical specialists/experts when required to ensure that interpretations of climatic and weather considerations used in managing and operating the road system reasonably reflect the most current scientific consensus regarding the climate and/or weather information.

Most BCMoTI staff members do not have the extensive training or experience in managing and assessing climate and weather information necessary to be considered expert in the field. As such, BCMoTI is highly likely to be a consumer of climate and meteorological and in some cases hydrotechnical information, relying on government agencies and other authorities to provide information for use within their ongoing activities.

Assessing climate information can be a technically demanding activity requiring a significant level of professional expertise to understand the subtleties of the information. On the other hand, climate and weather specialists and outside hydrotechnical specialists may not have a detailed understanding of the nature of BCMoTI activities and may find it difficult, without guidance, to provide climate and weather and hydrotechnical information that is meaningful to BCMoTI staff and contractors.

b) Application

- For key projects, establish multidisciplinary teams to assist in climate change vulnerability risk assessment

- Multidisciplinary teams should comprise, as appropriate:

  - Fundamental understanding of risk and risk assessment processes
  - Directly relevant engineering/design knowledge of the infrastructure
  - Climatic and meteorological and hydrotechnical expertise/knowledge relevant to the region
  - Hands-on operation experience with the specific infrastructure
  - Hands-on management knowledge with the specific infrastructure
  - Local knowledge and history, especially regarding the nature of previous extreme weather events, their overall impact in the region and approaches used to address concerns

7.2.4 Work with Qualified Climate and Meteorological Professionals

a) Interpretation

BCMoTI staff should work with climate (including climate change) and meteorological specialists/experts to ensure that interpretations of climatic and weather considerations used in management, design, operations and maintenance reasonably reflect the most up-to-date climate and weather information.

It is important to filter climate and climate change information through locally relevant climate and meteorological expertise. Climate experts from outside of a region might overlook or underestimate the impact of unique local weather phenomena. Climate and weather specialists may require detailed understanding of the characteristics of the infrastructure and may find it difficult, without guidance, to provide climate and weather information that is meaningful to the specific infrastructure under consideration.

Climate and weather information often may contain embedded uncertainties or sensitivities. Climate professionals are aware of these issues and can help BCMoTI staff come to grips with the overall quality of the information they are being provided. Furthermore, BCMoTI staff could potentially apply climate and weather information in ways that are completely inappropriate based on the methodological limitations of the processes used to develop that information.

BCMoTI staff should work with climate and weather specialists to gain a fulsome understanding of the strengths and limitations of the information they are using. Armed with this understanding, they will be equipped to incorporate appropriate measures within their own work to accommodate the quality of the information they are using.

b) Application

- List climate information needs in terms of parameters that are listed in codes, standards, guidelines and "rules of thumb" as well as other information that is not formally codified within codes, standards, etc. but are nonetheless relevant to the work.
    - Develop the current climate profile based on analysis of historical weather data
    - Use the current baseline to establish a foundation for future climate projections over the service life of the system
- For this climate information identify the:
    - Associated uncertainties with the information
    - Assumptions made
    - Data sources
    - Relative differences between current climate data derived from measured meteorological data and projected climate information based on modeling
- Review information accessed from climate and weather databases with regional climate and/or meteorological specialists to ensure that relevant information about extreme events has not been expunged from the record
- Assess the criticality of the impact of the climate information on the overall design and function of the system
- Assess if the climate information and factors have undergone recent review/update in light of climate change

- Review the climate information and factors with climate professionals to assess the applicability of the information and factors over the anticipated service life of the design

- Based on professional judgment, add appropriate safety factors or margins to address anticipated climate change conditions

7.2.5 Work with Qualified Hydrology Professionals and Hydrotechnical Engineers

a) Interpretation

Hydrology professionals are necessary for determining the design flow conditions either at specific project locations or at a regional level. Hydrotechnical engineers are generally responsible for conducting a hydraulic analysis in order to determine what impact the design flow conditions will have on the specific infrastructure under consideration. It is common for a hydrotechnical engineer to perform both the hydrologic and hydraulic analysis on standard MoTI management, design, operations or maintenance projects. It is important for hydrotechnical engineers to conduct a thorough site history and a site visit in order to properly understand the local conditions as well as validate their analysis.

It is the responsibility of hydrology professionals and hydrotechnical engineers, whether BCMoTI staff or otherwise, to ensure that interpretations of hydrological considerations used in management, design, operations and maintenance reasonably reflect the most up-to-date hydrologic information. Internal hydrological capacity is important, as retaining external specialists to assist in routine design and operational work could be prohibitively expensive.

b) Application

- Update regional peak flow analyses for the province

- Update rainfall intensity duration frequency (IDF) curves for the province

    - Where possible, account for the potential impacts of climate change

- When conducting hydrologic analyses, give consideration to the potential impacts of climate change specific to the region and/or watershed as applicable

    - This may be accomplished both qualitatively (describing potential changes in processes, such as receding glaciers) and quantitatively, as applicable

- Execute hydrologic analyses using more than one method (e.g. regional analysis, estimates from a proxy watershed, hydrologic modelling, rational method) to assess the convergence/divergence of estimates

- When conducting hydrological analysis identify and account for the uncertainties associated with the work. This is similar to the uncertainty analysis conducted by the climate and meteorological specialist to provide context to the information derived from the analysis

  - When applying results from hydrological analysis, include information about the associated uncertainties
  - Modify or adjust safety factors arising from the hydrological analysis based on the uncertainty information provided, as appropriate

- Establish an understanding of how the dominant processes generating annual peak flows in different areas of the Province may change in the future

  - Use the historic climate simulation as a baseline reference
  - Process may include, but are not limited to spring snowmelt, spring/summer rainfall, fall/winter rainfall, rain on snow, combined events, subsequent events, etc.

- Consider adjusting bridge or culvert freeboard allowances as buffers for gradually increasing flows related to climate change. Freeboard has traditionally been used to accommodate:

  - Uncertainty in predicting flows and water levels
  - Ice and debris passage
  - Aggradation
  - Navigation requirements

- Consider formally redefining the concept of 'clearance' at culverts and bridges, breaking it into components such as:

  - Ice, debris passage
  - Aggradation allowance
  - Model sensitivity allowance (to account for potential errors in channel roughness, model boundary conditions, hydrological flow predictions, etc.)
  - Climate change allowance (to account for potential increases in flow)
  - Navigation requirements

- Perform sensitivity analysis to assess impact of variations in assumptions and uncertainties

7.3 Process

7.3.1 Provide Risk Assessment Tools and Ensure that Staff are Trained in their Use

a) Interpretation

In the BCMoTI and Canada-wide vulnerability risk assessments that we reviewed, the primary risk assessment tool was the PIEVC Protocol[1], developed under the auspices of Engineers Canada. This tool guides staff and contractors through the risk assessment process from project concept through to an evaluation of adaptation options and can include weighting for social, environmental and economic factors.

The Engineers Canada tool is one of a number of tools and methodologies that have been developed to assess the impact of climate change through risk assessment. Risk assessment has been a common practice in many engineering disciplines for many years. Hazards and Operability (HazOps) assessments are routinely conducted on industrial processes for the purpose of identifying criticalities. Climate change and associated risks warrant similar evaluation.

Not every staff member or contractor may be conversant with risk assessment methodologies. Where this is the case, the BCMoTI should encourage staff and contractors to consult with professionals that do have risk assessment expertise.

b) Application

- BCMoTI staff and contractors should be encouraged to develop working skills with a range of risk assessment tools, as appropriate to the project
    - Establish awareness of the range and applicability of risk assessment tools
    - Where appropriate, pursue professional development and training in risk assessment tools and approaches relevant to tasks
- Where the staff member or contractor does not have sufficient expertise with a particular risk assessment tool deemed appropriate for an application, they should seek guidance from qualified professional practitioners that do have the expertise

[1] Engineers Canada, ***PIEVC Engineering Protocol for Infrastructure Vulnerably Assessment and Adaptation to a Changing Climate***, Revision 10, March 2013

7.3.2 Use Risk Management to Address Uncertainties

a) Interpretation

Assessing climate change impacts on infrastructure systems is a risk management process. Staff and contractors will use projections of future climate and assign measures of the likelihood of those projected futures and the seriousness of the impacts of those changes on the systems for which they are responsible. This is the very definition of risk management.

Climate information includes embedded uncertainties that that can be incorporated into risk assessment and management approaches in mitigating future adverse outcomes. Risk management is a standard engineering and management practice, normally applied through using safety factors and margins or other methods of mitigating potential design and operations risks.

In this application, BCMoTI staff and contractors should apply these approaches to address the evolving risk from uncertain climate futures. In order to address potential climate change impacts, staff and contractors should develop a comprehensive understanding of risk management techniques or consult, as appropriate, professionals who have those skills.

b) Application

- BCMoTI staff and contractors should be encouraged to develop competence in risk management
  - Establish awareness of the range and applicability of risk management tools
  - Where appropriate, they should be encouraged to pursue professional development and training in risk management tools
- Where BCMoTI staff or contractors do not have sufficient expertise in risk management, they should seek guidance from qualified practitioners that do have the expertise
- As appropriate, BCMoTI should retain the services of professional practitioners with risk management expertise to assist in the review of climate risks
- As appropriate, build risk management into ongoing management, design, operation, maintenance, planning, and procurement practices
  - Different tools may be applicable for these different activities
  - Staff and contractors should be encouraged to maintain a working knowledge of the risk management approaches that are appropriate at each stage of a project
- As appropriate, consult with the broad range of stakeholders/users of engineered systems to assess the overall risk tolerance levels for the systems

- Risk management is a multi-disciplinary and multi-stakeholder process. Every party has unique and valuable insights that should be considered in the risk management process

7.3.3 Incorporate Climate Change Adaptation Measures into Planning Cycles

a) Interpretation

BCMoTI staff and contractors should ensure that they have reasonably considered the impact of changing weather and climate conditions over the entire service life of their projects.

BCMoTI staff and contractors develop and operate highway systems that must be resilient to changing climate conditions in the future. Climate conditions observed in the past or even today may not be sustained throughout the entire service life of a project. Climate change is a long-term issue affecting infrastructure. Climate models can project changes in climate parameters twenty, forty, even one hundred years into the future. The uncertainty in climate projections increases as the time horizon for those projections is extended farther into the future.

The refurbishment of road systems allows for checkpoints throughout their service life. If there are no refurbishment opportunities, then the evaluation of climate change in the initial design becomes more critical, as the system will have to stand for a very long time without any routine opportunities to adjust. Even in these cases, many climate risks can be addressed through enhancements in operations, maintenance and management procedures and practices.

BCMoTI staff members and contractors should capitalize on refurbishment opportunities balanced with available funding to review, revise and adapt to climate during the life of a project. Replacement in-kind may not be the appropriate response for refurbishing a system. BCMoTI staff members and contractors should evaluate the possibility that climate change may have contributed to the observed wear and tear on the project and upgrade the system appropriately.

Furthermore, BCMoTI staff members and contractors should consider not only the useful life of the project, but also the useful life of the refurbishment activities with respect to climate change impacts. Even if the system elements being refurbished are not presently seeing the impact of climate change, it is possible that they will experience those impacts before the next refurbishment is planned. BCMoTI staff members and contractors should contemplate those impacts in refurbishment planning in the same way that they would consider these factors for a new project.

In some ways, anticipating climate change on a refurbishment plan is simpler than it would be for the entire life of a project. The climate change projections would be on a shorter time horizon and would therefore have much less uncertainty associated with them. This would provide the BCMoTI staff members and contractors with much greater confidence to recommend appropriate adaptive responses.

Similarly, professionals in operations, maintenance and planning functions should ensure that they allocate appropriate resources to allow other professionals the scope to incorporate appropriate climate change adaptive measures into their respective works. Projects that do not include climate change consideration in their scope may seem to be less costly for initial procurement. However, projects with no scope for incorporating climate risk are likely to incur much higher costs associated with renewing non-resilient designs over the life of the system.

b) Application

- During the design phase of a project, maintain a record of any reviews of climate and/or meteorological vulnerability risk assessment conducted
  - Identify any adjustments made to the design based on climate considerations
  - Identify the basis for any adjustments made to the design based on climate considerations
  - Identify the economic impact of changes made to design based on climate considerations
  - Identify how the adjustments address the full service life cycle of the engineered system
- During refurbishment planning and design, maintain a record of any reviews of climate and/or meteorological vulnerability risk assessment conducted
  - Identify any adjustments made to the refurbishment design/plan based on climate considerations
  - Identify the basis for any adjustments made to the refurbishment design/plan based on climate considerations
  - Identify the economic impact of changes made to the refurbishment design/plan based on climate considerations
  - Identify how the adjustments address the full service life cycle of the refurbishment design/plan

7.3.4 Mandate Adaptation to Climate Change Considerations in Ongoing Activities

a) Interpretation

BCMoTI staff members and contractors should ensure that an understanding of changing climate and weather is integrated into the ongoing design, operation, maintenance, planning and procurement activities for which they are responsible.

Understanding the potential of adverse impacts from climate change is especially relevant for staff who are in significant decision-making positions. These decision-makers establish the environment within which other staff members and contractors must function. They should establish organizational objectives that incorporate the recognition that climate change may require practice that may exceed codes, standards and professional guidelines.

For example, when an event occurs, such as one involving Federal Disaster Financial Assistance Arrangements (DFAA), there is a notion during the emergency response phase to re-establish the pre-existing infrastructure. Given the lifespan of the infrastructure, replacement in kind may not be the best choice when considering subsequent events including climate change. Thus a revised design capacity may be required for the infrastructure.

During the recovery phase of disaster type events, some infrastructure may be designed and replaced with capacity to accommodate future climate change. However, these are usually the larger structures such as bridges. Smaller infrastructure components such as culverts may not be designed for additional loading from climate changes and thus could be under capacity for current and future conditions. This is an area that may require policy review. That is, should the infrastructure be considered vulnerable in the future due to climate change, then the replacement design should allow for higher capacity and increased DFAA funding would need to be applied, or incremental funds above DFAA funding may be required from the infrastructure owner. Within this type of policy environment reasonable increases in project costs that address climate adaptation objectives may be warranted. By establishing this environment, the decision-maker enables their subordinates and contractors to take reasonable actions within a risk management environment (risk and budget considerations) to address climate change in their work.

Similarly, staff that work in procurement positions, setting project specifications and reviewing competitive proposals should also be conversant with potential climate change impacts on their projects. Foregoing addressing climate change impacts in project scope will not lead to life-cycle cost avoidance, and will likely lead to unidentified and unaddressed design vulnerabilities. They should incorporate within their systems ways and means to accommodate reasonable modifications in scope and pricing to adapt to projected climate changes.

Finally, staff in maintenance and operation functions will likely see the impact of creeping climate change on a continual basis. They should not only work to ensure the sustained operation of the systems for which they are responsible, but should also clearly identify the climate impacts to which they are responding and inform relevant authorities within the Ministry.

Over time, the knowledge to incorporate appropriate climate change information into resources, such as, codes, standards and guidelines will address climate change impacts.

b) Application

- Maintain a record of actions undertaken within ongoing practice that facilitate addressing climate change issues

- Specifications should explicitly include consideration of climate change

    - Consider the long term sustainability of the infrastructure
    - In procurement, consider margins to accommodate climate adaptation measures
    - In management, consider recommendations that address climate risks

- Revise operations, maintenance, management and DFAA procedures and practices to consider future climate risks

- Explicitly identify the requirement for identifying climate change and adaptation measures in contracted engineering work

7.3.5 Monitor Data used in Codes and Standards

a) Interpretation

BCMoTI staff members should review standards used within their activities to ensure that these standards reasonably represent the current climate data, and allow for changes in future climate.

Given the potential impact of changing climate on highways, it may no longer be appropriate for BCMoTI staff and contractors to simply rely on the veracity of codes, standards and professional guidelines that include embedded climate assumptions.

BCMoTI staff and contractors should ensure that they routinely review and challenge the tools that they use in their activities. The intent is to ensure that knowledge gained through ongoing review of the codes and standards is shared broadly within BCMoTI. Once staff or contractors identify a concern in a code, standard or professional guideline, they should share their findings throughout the organization and, as appropriate, within the broader community.

The obligation to review tools also covers those used by staff on an ongoing basis, such as procedures, codes of practice, rules of thumb, etc. BCMoTI staff members or contractors should routinely evaluate these tools within the context of each situation in which they are applied. If the staff member or contractor identifies even small modifications to their tools, they should document the changes and share them within the group who would normally use the tools.

b) Application

- Ensure that work is conducted applying the most up-to-date revision of relevant codes and standards

- Create a file of adjustments made to codes, standards and assumptions to accommodate changing climate. As appropriate, communicate adjustments:

    - Within the department, division or organization
    - To professional societies, associations or groups
    - To standards organizations and regulators who developed the codes and standards