Climate Change Engineering Vulnerability Assessment

B.C. Yellowhead Highway 16
Between Vanderhoof and Priestly Hill

Rev 4
April 27, 2011

Contents

Figures

Appendices

1 Introduction

1.1 Background

The British Columbia Ministry of Transportation and Infrastructure is responding to issues of climate variability in its highway design, operation and maintenance processes by undertaking pilot climate change engineering vulnerability assessments of highway segments within the Province of British Columbia. The assessments evaluate highway structures in different geographical areas and climate regimes, given forecast changes in climate conditions. The goal is to understand how climate variability may impact current highway structures, and to prepare and adjust design, operation and maintenance criteria for future climate conditions.

These case studies rely on partnerships with:

- Engineers Canada, and their assessment protocol;
- The Pacific Climate Impacts Consortium at the University of Victoria and their climate analysis expertise and forecasts;
- Other government department; and
- Especially the staff within the BC Ministry of Transportation and Infrastructure, and their knowledge and experience.

The Yellowhead Highway, that is the focus of this study, as well as the previous Coquihalla Highway study and any subsequent studies executed by the Ministry are intended to assist in planning for, and adapting to potential climate change. The Ministry will address results from examining forecast climate and infrastructure interactions, including findings and recommendations and any required remedial action. These studies will ensure highway design standards and guidelines, as well as operation and maintenance considerations anticipate forecast climate variability.

The analysis in this report follows the Engineers Canada – Public Infrastructure Engineering Vulnerability Committee (PIEVC) five-step protocol to identify vulnerability and adaptation issues on the Yellowhead Highway 16 in British Columbia. This analysis developed future climate risk profiles of transportation infrastructure on a section of the Yellowhead Highway between Priestly Hill (east of Burns Lake) and Vanderhoof in central British Columbia. This was the second case study by British Columbia Ministry of Transportation and Infrastructure using the PIEVC protocol: the first was a study of a section on the Coquihalla Highway.

In addition, a more extensive analysis was conducted on some components that were the highest risk elements identified in the study. This required a calculation of the component’s load and capacity in order to identify potential vulnerability and adaptability to forecast future climate variability.

The specific risk interactions considered for more detailed analysis were between drainage structures and high rainfall events, bridges and high temperature, and a discussion on pavement asphalt cement (AC) grades and temperature ranges.

The drainage interactions were examined using hydrotechnical analysis. The work found that culverts and catch basins could be overloaded by forecast increases in rainfall. This indicates vulnerability. BC MoTI may need to examine and update highway drainage design and maintenance policies and procedures for forecast future climate conditions.

The study also looked at concrete bridges and their interaction with high temperature. These structures may exhibit a slight vulnerability with very high temperatures, just above their design specification. Therefore, depending on the extreme high temperatures forecast in the future, monitoring this situation is recommended.

Road pavement AC grade based on temperature ranges was also examined in this study. AC pavement grade choice has been based on historical air temperature ranges measured on given roadways. Based on this study there was a 13°C difference between air and road surface temperatures under hot conditions. This may require adjusting pavement grades based on future, not historical temperature ranges in design specifications.

The Yellowhead highway study indicated that vulnerability mainly results from future forecast rainfall increases. The type of surface terrain can exacerbate the affect on drainage considerations. In the Vanderhoof region, logging and pine beetle and forest fire damage to trees can change the natural surface cover. Increased runoff that will eventually be carried to the highway requires structure capacity designed to accommodate it.

Based on the work conducted in this engineering vulnerability assessment, the team concluded that, overall, except for some potential future drainage situations, the infrastructure components on the Yellowhead Highway are generally resilient to forecast future climate variability.

The Yellowhead Highway 16 case study exhibited similar findings as the previous Coquihalla Highway 5 case study. In both studies, future forecast extreme rainfall events had the potential to cause vulnerability to highway infrastructure drainage components.

1.2 Methodology

Engineers Canada, the business name for the Canadian Council of Professional Engineers, established the Public Infrastructure Engineering Vulnerability Committee (PIEVC) to oversee the planning and execution of a broad-based national assessment of the engineering vulnerability of Canadian public infrastructure to changing climatic conditions.

This National Engineering Vulnerability Assessment is a long-term project to evaluate the changes anticipated to the risks to Canadian public infrastructure posed by climate change. PIEVC established roads and associated structures vulnerability as one of four priorities for review. The other priority areas include stormwater and wastewater, buildings, and water resource systems. The National Engineering Vulnerability Assessment will lead to recommendations concerning the review of infrastructure codes, standards and engineering practices to accommodate future climate change anticipated over the service life of these categories of infrastructure.

For the purposes of this study, engineering vulnerability 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. The 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; and
- Built-in capacity of infrastructure to absorb any net negative consequences from the predicted changes in climatic conditions.

Therefore, engineering vulnerability assessment requires assessment of all three elements.

The principal method being used to develop a national picture of the engineering vulnerability of infrastructure to climate change is through selective case studies of individual infrastructures or infrastructure systems.

This assessment not only requires a definition, and projection of climatic design parameters, but also the definition of the characteristics and components of the infrastructure, which make them more or less vulnerable to climate change. These can include, but are not limited to:

- Age and condition of the infrastructure;
- Maintenance practices;
- The rate at which system is upgraded or replaced;
- System characteristics;
- Geographical limitations on the system;
- Other factors affecting sustainability of the current system (e.g. population growth);
- The variation in design standards across the country;
- Policies and incentives; and
- Other factors that may be identified.

The Ministry of Transportation and Infrastructure, Province of British Columbia (BC MoTI) has agreed to work with Engineers Canada and the PIEVC to assess the engineering vulnerability of a stretch of B.C. Highway 16 between Vanderhoof and Priestly Hill.

1.3 Purpose

The principle objective of this case study was to identify those components of this section of B.C. Highway 16 that are at risk of failure, loss of service, damage and/or deterioration from extreme climatic events or significant changes to baseline climate design values.

The assessment was carried out using:

- ***The PIEVC Engineering Protocol, Version 9, April 2009.***

The results of this case study will be incorporated into a national knowledge base and analyzed with other case studies to develop recommendations around reviews of codes, standards and engineering practices.

1.4 Study Scope and Timing

The scope of the assessment encompassed the current design, construction, operation and management of this infrastructure as well as planned upgrades or major rehabilitation projects.

This project assessed the vulnerability/adaptive capacity of the highway infrastructure including the drainage system.

This project was completed over the period October 1, 2010 through February 28, 2011 and contemplated climate change effects for two climate change projection horizons – 2050 and 2100.

1.5 PIEVC Engineering Protocol for Climate Change Infrastructure Vulnerability Assessment

The Yellowhead Highway 16 climate change vulnerability assessment followed the Protocol developed by PIEVC. The Protocol provides a framework to define, evaluate, and prioritize information and relationships regarding climate change impacts on the infrastructure.

Findings supported by this framework can be used to support decision-making on future operations, maintenance, planning, and development or potential upgrading or rehabilitation of the infrastructure.

The Protocol outlines five steps in the assessment process, as follows:

- Step 1: Project Definition
- Step 2: Data Gathering and Sufficiency
- Step 3: Risk Assessment

- Step 4: Engineering Analysis
- Step 5: Recommendations

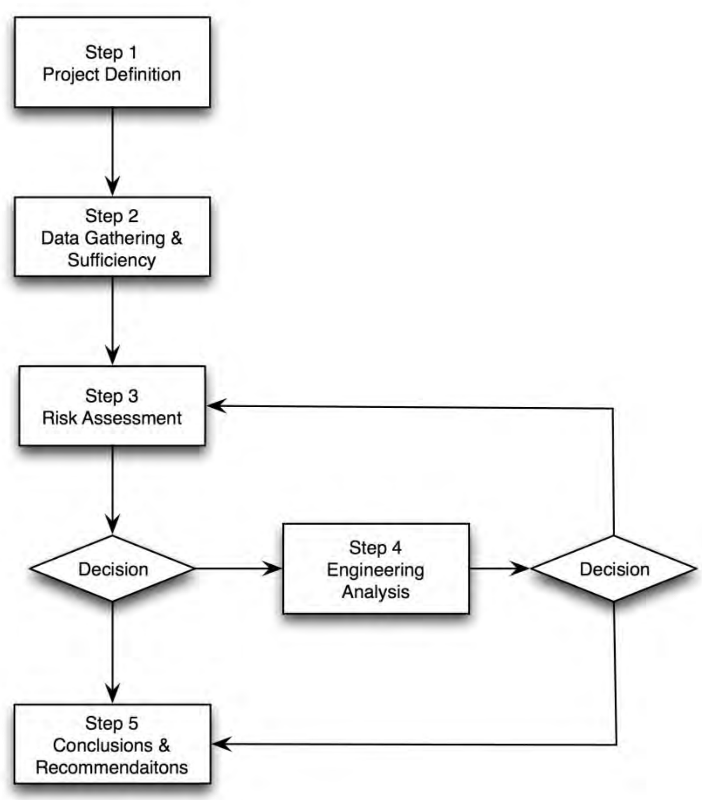
Part I of the most recent version of the Protocol, used for this study, is presented in **Appendix A**. The complete Protocol is available under license from Engineers Canada.

Each of the five steps has an associated worksheet that guides the practitioner through the assessment.

This report follows closely the steps outlined in the Protocol.

A flowchart outlining the process is presented in **Figure 1.1**. In the following sections we briefly summarize the evaluation process outlined by the Protocol.

Figure 1.1: Process Flowchart for Application of PIEVC Protocol



1.5.1 Step 1 - Project Definition

In this step the evaluation team defines the boundary conditions for the vulnerability assessment.

The team:

- Develops a general description of:
    - The infrastructure;
    - The location;
    - Historic climate;
    - Load;
    - Age;
    - Other relevant factors; and
- Identifies major documents and information sources.

1.5.2 Step 2 - Data Gathering and Sufficiency

In this step the team provides more definition about:

1. Which parts of the infrastructure will be assessed; and
2. The particular climate factors that will be considered.

This step comprises two key activities:

1. Identification of the features of the infrastructure that will be considered in the assessment:

    - Physical elements of the infrastructure;
        - Number of physical elements;
        - Location(s);
    - Other relevant engineering/technical considerations:
        - Material of construction;
        - Design parameters;
        - Age;
        - Importance within the region;
        - Physical condition;
    - Operations and maintenance practices;
    - Operation and management of the infrastructure;
        - Insurance considerations;
        - Policies;
        - Guidelines;
        - Regulations; and
        - Legal considerations.

2. Identification of applicable climate information. Sources of climate information include, but are not limited to:

- The National Building Code of Canada, Appendix C, Climate Information;
- Intensity - Duration – Frequency (IDF) curves;
- Flood plain mapping;
- Regionally specific climatic modeling;
- Heat units (i.e. degree-days) (i.e. for agriculture, HVAC, energy use, etc.); and
- Others, as appropriate.

The team is required to exercise professional judgement based on experience and training. This is an interdisciplinary process requiring engineering, climatological, operations, maintenance, and management expertise. The team must ensure that the right combination of expertise is represented either on the assessment team or through consultations with other professionals during the execution of the assessment.

1.5.3 Step 3 - Risk Assessment

In this step the team identifies the interactions between the infrastructure, the climate and other factors that could lead to vulnerability. These include:

- Specific infrastructure components;
- Specific climate change parameter values; and
- Specific performance goals.

The Protocol requires the team to identify which elements of the infrastructure are likely to be sensitive to changes in particular climate parameters. They will be required to evaluate this sensitivity in the context of the performance expectations and other demands that are placed on the infrastructure. Infrastructure performance may be influenced by a variety of factors and the Protocol directs the team to consider the overall environment that encompasses the infrastructure.

Based on these parameters the team performs a risk assessment of the infrastructure's vulnerability to climate change. The interactions identified are evaluated based on the professional judgement of the assessment team. The risk assessment will identify areas of key concern.

The team will identify those interactions that need further evaluation. The assessment process does not require that all interactions be subjected to further assessment. In fact, in the majority assessments most of the interactions considered will ultimately be eliminated from further consideration. Some interactions may clearly present no, or negligible, risk. Some interactions may clearly indicate a high risk and a need for immediate action. Those interactions that do not yield a clear answer regarding vulnerability may be subjected to the further engineering analysis.

At this stage, the team will also assess data availability and quality. If professional judgment identifies a potential vulnerability that requires data that is not available to the assessment team, the protocol requires that the team revisit Step 1 and/or Step 2 to acquire and refine the data to a level sufficient for risk assessment and/or engineering analysis. The team may determine that this process requires additional work outside of the scope of the assessment. Such a finding must be identified in the recommendations outlined in Step 5.

This is a key decision point in the Protocol. The practitioner is required to determine:

- Which interactions require additional assessment;
- Where data refinement is required; and
- Initial recommendations about:
    - New research;
    - Immediate remedial action; or
    - Non-vulnerable infrastructure.

1.5.4 Step 4 - Engineering Analysis

In Step 4 the team conducts focused engineering analysis on the interactions requiring further assessment, as identified in Step 3.

The Protocol sets out equations that direct the team to numerically assess:

- The total load on the infrastructure, comprising:
    - The current load on the infrastructure;
    - Projected change in load arising from climate change effects on the infrastructure;
    - Projected change in load arising from other change effects on the infrastructure;

- The total capacity of the infrastructure, comprising:
    - The existing capacity;
    - Projected change in capacity arising from aging/use of the infrastructure; and
    - Other factors that may affect the capacity of the infrastructure.

Based on the numerical analysis:

- A vulnerability exists when ***Total Projected Load*** exceeds ***Total Projected Capacity***; and
- Adaptive capacity exists when ***Total Projected Load*** is less than ***Total Projected Capacity.***

At this stage the team makes one final assessment about data availability and quality. If, in the professional judgement of the team, the data quality or statistical error does not support clear conclusions from the Engineering Analysis, the Protocol directs the team to revisit Step 1 and/or Step 2 to acquire and refine the data to a level sufficient for robust engineering analysis. The team may determine that this process requires additional work outside of the scope of the assessment. Such a finding must be identified in the recommendations outlined in Step 5.

Once the team has established sufficient confidence in the results of the engineering analysis, the Protocol reaches another key decision point. The team must decide to either:

- Make recommendations based on their analysis (Step 5); or
- Revisit the risk assessment process based on the new/refined data developed in the engineering analysis (Step 3).

1.5.5 Step 5 - Recommendations

In Step 5 the team is directed to provide recommendations based on the work completed in Steps 1 through 4. Generally, the recommendations will fall into five major categories:

- Remedial action is required to upgrade the infrastructure;
- Management action is required to account for changes in the infrastructure capacity;
- Continue to monitor performance of infrastructure and re-evaluate at a later time;
- No further action is required; and/or
- There are gaps in data availability or data quality that require further work.

The team may also identify additional conclusions or recommendations regarding the veracity of the assessment, the need for further work or areas that were excluded from the current assessment.

1.6 Project Team

Climate change engineering vulnerability assessment is a multidisciplinary process requiring a wide range of engineering, construction, operation, and maintenance skills and knowledge. Furthermore, the team must include deep knowledge of climatic and weather conditions relative to the project location. For the Yellowhead Highway 16 project, BC MoTI personnel provided the primary technical and operations infrastructure knowledge. BC MoTI drove the project and was responsible for identifying and assessing the likely response of the infrastructure to projected climate change.

Staff from the Pacific Climate Impacts Consortium (PCIC) provided climate change data and projections as well as ongoing advice regarding the interpretation of climatic data.

The membership of the Project Team is outlined in **Figure 1.2**.

Figure 1.2: BC MoTI Project Team Membership

Area of Responsibility	Team Member
Chief Engineer	Dirk Nyland
Regional Director	Rick Blixrud
Regional Manger	Gord Wagner

Figure 1.2: BC MoTI Project Team Membership

Area of Responsibility	Team Member
Project Manager	Jim Barnes
Geotechnical	Ian Pilkington (Chief) Bill Eisbrenner (Manager) Crystal Lacher Tim Meszaros
Design & Traffic	Ed Miska (Section Head) Nini Long (Manager) Darwin Tyacke
Structural	Ron Mathieson
Operations & Maintenance	Reg Fredrickson (Director)
Hydrology/Hydrotechnology	Mike Feduk Dickson Chung Simon Walker
District Technician	Doug Elliot
Environmental	Daryl Nolan Greg Czernick Thomas White
Area Manager	Tom Lupton

PIEVC provided ongoing advice to the project through a project advisory committee comprised of active PIEVC technical advisors.

The membership of the Project Advisory Committee is outlined in **Figure 1.3**.

Figure 1.3: Project Advisory Committee

Organization	Team Member
Pacific Climate Impact Consortium	Gerd Buerger
Pacific Climate Impact Consortium	James Hiebert
City of Edmonton	Hugh Donovan
Chief Engineer - NL	Brandon MacDonald
Environmental Engineer - NL	Michael Carrol
Project Manager – Transport Canada	Mark Thompson
Engineers Canada	David Lapp

BC MoT retained Nodelcorp Consulting Inc. to facilitate the process and prepare this report.

The membership of the Facilitation and Reporting Team is outlined in **Figure 1.4**.

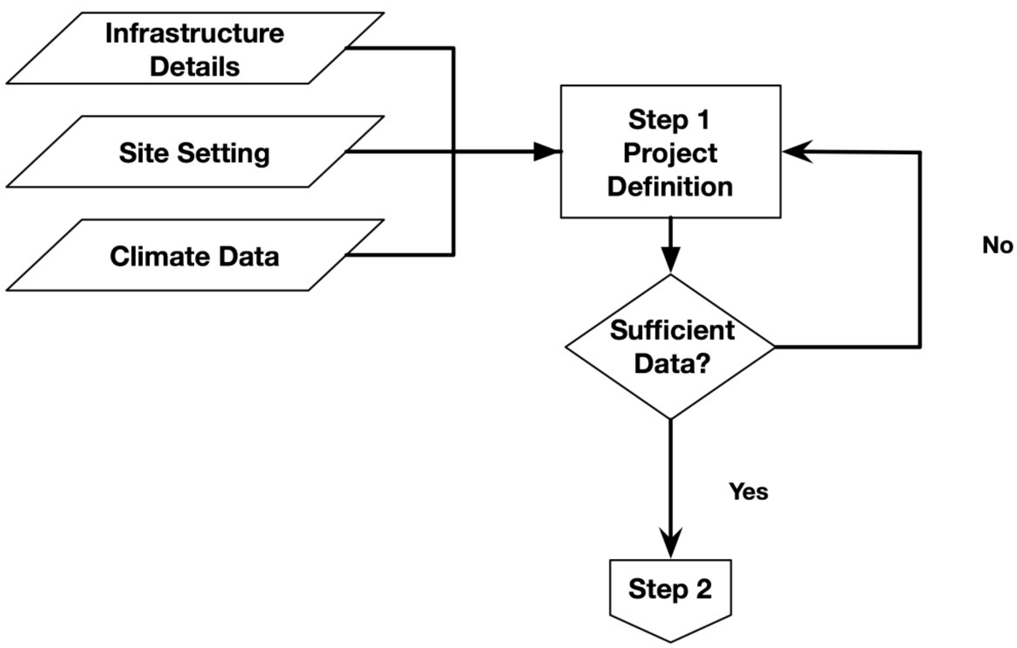
Figure 1.4: Facilitation and Reporting Team

Role	Team Member
Facilitation - Reporting	Joel R. Nodelman
Facilitation – Reporting	Joan Y.H. Nodelman

2 Step 1 – Project Definition

The team applied the Protocol process to define the project boundary conditions in space and in time. The process followed the steps identified in the process flowchart presented in **Figure 2.1**.

Figure 2.1: Project Definition Process Flowchart



2.1 Identify Infrastructure

2.1.1 Pre Screening

In order to evaluate and compare potential sites that could be used in an assessment of roadway and associated infrastructure vulnerability due to climate change, BC MoTI developed a list of site selection criteria. Each criterion was assigned a weighting that indicated its relative importance in the site selection process.

For the purposes of the site evaluation, the team selected potential sites that included a section of roadway covering approximately 30 km to 40 km.

For each potential site, the BC MoTI Team assigned a rating between 0 (poor) and 5 (excellent) for each criterion on the "Site Rating" spreadsheet. This rating indicated the degree to which the site was a good candidate based on those specific criteria.

Once a site had been rated, a score for the site was calculated based on the criteria weighting and the site ratings.

The overall scores for each section of highway are presented in **Figure 2.2**.

The detailed analysis used by BC MoTI to establish the infrastructure for the study is presented in **Appendix B**. The completed Worksheet 1 from the Protocol and supporting documentation is presented in **Appendix C**.

Figure 2.2: Preliminary Screening of Potential Sites

Site	Score
Hwy 3, Kootenay Pass (between Salmo and Creston)	129
Hwy 31, Meadow Creek to Trout Lake	126
Hwy 16, Burns Lake to Smithers	130
Hwy 29, Chetwynd to Charlie Lake	117
Hwy 14, Sooke to Port Renfrew	111
Hwy 5, Coquihalla (between Hope and Merritt)	154
Hwy 3, Paulson Pass (between Christina Lake and Junction with Hwy 3B)	119
Hwy 16, Terrace to Prince Rupert	149

Based on the analysis completed by the BC MoTI Team, the stretch of Coquihalla Highway between Hope and Merritt received the highest overall rank and was selected as the focus of the first infrastructure climate change vulnerability assessment conducted by BC MoTI. That assessment was completed in March 2010.

The second highest score was given to the stretch of Highway 16 between Terrace and Prince Rupert. However, BC MoTI concluded that stretch of highway exhibited very similar climatic and geographical features to the Coquihalla Highway.

BC MoTI wished to demonstrate an application of the Protocol under different climatic and geographical conditions. Based on this assessment, BC MoTI selected B.C. Yellowhead Highway 16 to the east of the Smithers section, for the focus of this current assessment. Priestly Hill is just east of Burns Lake. For the purposes of this vulnerability assessment, this section of highway was designated ***Highway 16 between Vanderhoof and Priestly Hill***.

This section of highway between Burns Lake and Vanderhoof, is located on a plateau and does not have the significant changes in elevation exhibited by the other two highway sections. The climate is also somewhat different, being in central BC, with coastal weather features, such as Pineapple Express, being attenuated by its inland location. The team concluded that these differences would ensure that an assessment on this stretch of highway could contribute new insight about the overall resiliency of BC highways to climate change.

Finally, BC MoTI chose this section of highway as their second demonstration project because of the availability of information and the knowledge base of the staff that would participate on the project.

2.1.2 Infrastructure Description

Vanderhoof, about 100 km west of Prince George on Yellowhead Highway 16, is the geographic centre of British Columbia. Prince George has a population of over 70,000. It is the largest city in northern British Columbia and is known as the "BC's Northern Capital". Situated at the confluence of the Fraser and Nechako Rivers, and the crossroads of Highway 16 and Highway 97, the city plays an important role in the province's economy and culture.

Many activities have been associated with the area including fur trading, mining, the railroad, lumber and mills.

The Yellowhead Highway in British Columbia runs from the eastern border with Alberta west through the Cariboo Mountains to Prince George, and through the Fraser Plateau, the Bulkley River Valley and the Skeena River Valley, before reaching the west coast at Prince Rupert. In 1942 the number '16' was assigned to the British Columbia portion of this road.

The Yellowhead Highway closely follows the path of the northern B.C. alignment of the Canadian National Railway and in 1947 the western end of the highway was moved from New Hazelton to the coastal city of Prince Rupert.

In the late 1960's and very early 1970's, Highway 16 was completed east from Prince George to the Yellowhead Pass (Tete Jaune Cache) with a series of construction and paving projects. If there was a link prior to 1970, it would have been not much more than a series of connected logging roads.

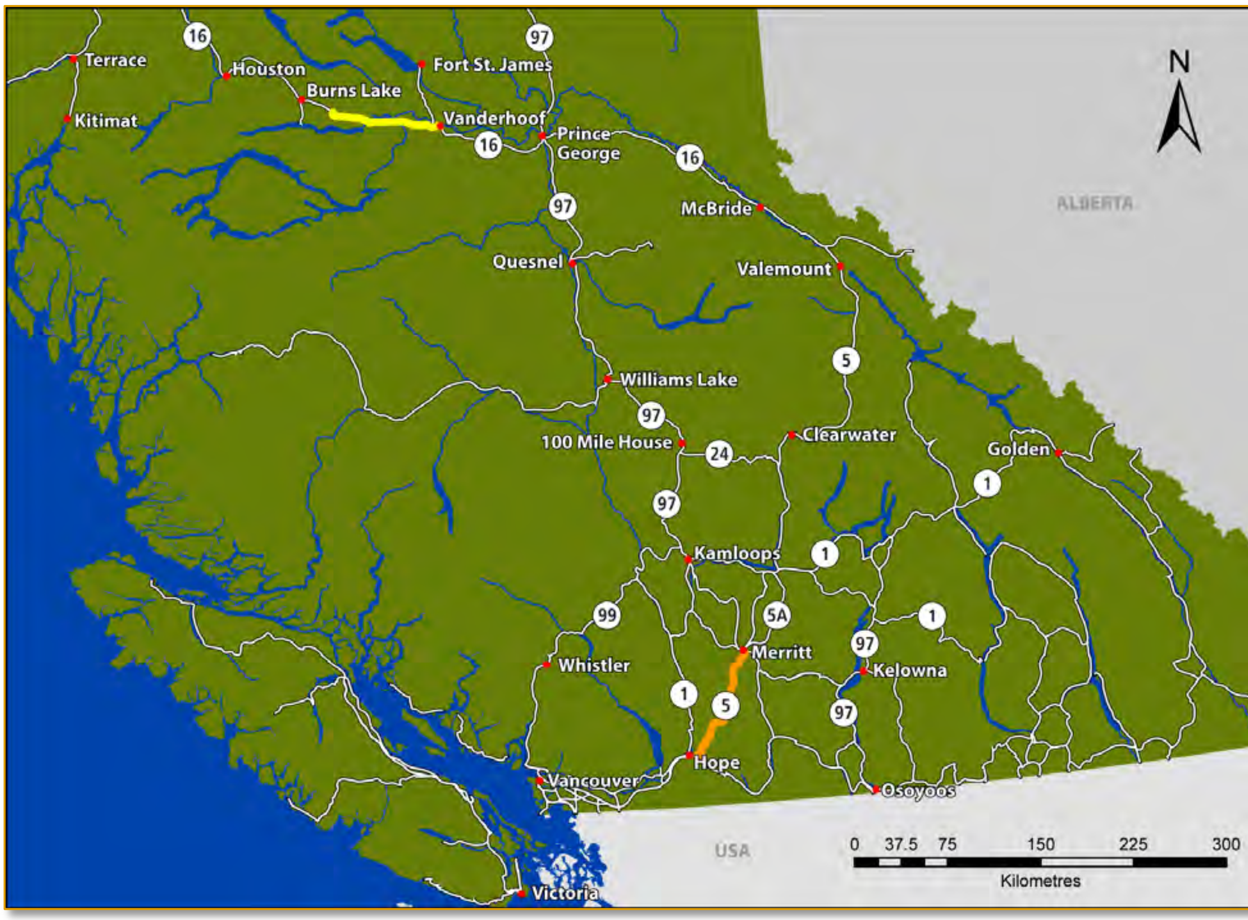
The original surfacing for Highway 16 west of Prince George is not well documented. It appears from the incomplete histograms that the first serious upgrading of the 155 km-long stretch between Prince George and Fraser Lake was carried out between 1953 and 1960 when 450 to 600 mm of pit run gravel was placed and then capped with a 75mm thick pulvi-mix (cold mix) pavement surface (the east 135 km) or a sealcoat surface (the west 20 km).

The pit run gravel was likely highly variable in quality and size, and it appears there is no identifiable processed (crushed) base course layer beneath the pavement. From 1960 to 1995, a number of pavement patches, pavement overlays (including asphalt base course mixes, recycled asphalt pavements, and conventional pavements), chip seals, sealcoats, and crack seals have been carried out. Pavement thicknesses range from 200mm to 450mm, with an average of about 300mm.

Although the pavement structures are highly variable throughout this stretch of road with largely unknown parameters for the structure components, the road surface is very strong and there are no observable or measurable strength deficiencies – largely due to the thick pavement. Consequently, rehabilitation work carried out over the last 15 years has mostly included hot-in-place recycling and sealcoat treatments to improve/preserve the existing surface rather than increase its thickness.

The location of the infrastructure is detailed in **Figure 2.3**.

Figure 2.3: Map of Infrastructure Location



The B.C. Section of the Yellowhead Highway runs from Alberta to the Pacific Ocean and was designated Highway 16 in 1942. The study section is on the Fraser Plateau in Central B.C.

2.2 Identify Climate Factors of Interest

2.2.1 Observations of Historic Climate Conditions

The study area contains many lakes, and has long, cold winters and short, hot summers. In past winters, the temperature was known to drop below -30° C for weeks; however this is not observed in recent times.

The January average temperature is −9.6 °C and there are an average of 38 days from December to February where the high reaches or surpasses freezing. Winter months in which Pacific air masses dominate may produce thawing on a majority of days, as in January 2006 when the mean daily maximum temperature was 1.5 °C.

On the other hand, Arctic air masses can settle over the city for weeks at a time. In rare cases, like January 1950, the temperature can stay well below freezing over a whole calendar month.

Summer days are warm, with a July high of 22.1 °C, but lows are often cool, with monthly lows averaging below 10 °C. The transitions between winter and summer, however, are short. There is some precipitation year-round, but February through April is the driest period. Snow averages 216 centimetres each year.

2.2.2 Climate Factors for Study

The team found that the identification of climate factors was a recursive process. Initially, the team identified an extensive list of potential climate factors. This list was defined in Worksheet 1 of the Protocol, which is presented in **Appendix C**. This initial listing was completed on November 24, 2010. As work progressed, the team refined the list of pertinent climate factors based on their understanding of relevant interactions between the climate and the infrastructure. Thus, the list of potential climate factors identified in Worksheet 1 was adjusted throughout the assessment process ultimately arriving at the list provided in **Figure 2.4**.

The team observed that the initial list of climate parameters was more extensive than was ultimately necessary to conduct a comprehensive risk assessment and streamlined the list accordingly. Furthermore, the team noted that some relevant parameters were very difficult to define to a level sufficient to draw substantive conclusions. These parameters were identified for further studies and analysis outside of this context of this assessment.

The team also identified a number of infrastructure indicators to aid in the assessment. These indicators are specific infrastructure requirements related to the identified climate parameters. For example, the team determined that not only was high temperature a potential factor in assessing infrastructure responses to climate, they also determined, specifically, that the infrastructure would likely adversely respond to temperatures in excess of 30^{o} C and that the number of days that the infrastructure experienced these conditions should be a consideration. These indicators were derived from design specifications and ongoing operation and maintenance considerations. The combination of climate parameter and infrastructure indicator provides sufficient definition for the team to assess specific infrastructure responses to the identified climatic condition.

Figure 2.4: Climate Parameters and Infrastructure Indicators Selected for the Risk Assessment

#	Climate Parameter	Infrastructure Indicator	Source	Comments
1	High Temperature	Day(s) with maximum temperature exceeding 35°C	S6-06 Clause 3.9 – Superimposed Deformations – temperature effects to be addressed in bridge design; maximum and minimum effective temperatures given	
2	Low Temperature	Day(s) with minimum temperature below -35° C	S6-06 Clause 3.9 – Superimposed Deformations – temperature effects to be addressed in bridge design; maximum and minimum effective temperatures given	
3	Average Temperature	Average Maximum Temperature Over 7 Days		Eliminated from the Assessment at the Workshop. Not relevant for this infrastructure assessment.
4	Temperature Variability	Daily temperature variation of more than 25 ° C	S6-06 Clause 3.9 – Superimposed Deformations – temperature effects to be addressed in bridge design; maximum and minimum effective temperatures given S6-06 Clauses 6.4 and 6.5 - Foundation design and Geotechnical investigation – consider temperature change effects	Eliminated from the Assessment at the Workshop. Not relevant for this infrastructure assessment.

Figure 2.4: Climate Parameters and Infrastructure Indicators Selected for the Risk Assessment

#	Climate Parameter	Infrastructure Indicator	Source	Comments
5	Freeze / Thaw	Number of days where maximum temperature > 0^{o} C and minimum temperature < 0^{o} C Not consecutive days. Concern is total number of events per year.	S6-06 Clause 8.11 – Durability – consider freeze-thaw deterioration of concrete S6-06 Clauses 6.4 and 6.5 - Foundation design and Geotechnical investigation – consider temperature change effects	
6	Frost / Frost Penetration	47 or more consecutive days where minimum temperature < 0^{o} C	S6-06 Clause 6.4.3 – Effects on structure – consideration shall be given to frost penetration. S6-06 Clauses 6.4 and 6.5 - Foundation design and Geotechnical investigation – consider frost penetration	
7	Total Annual Rainfall	406.7 mm		
8	Extreme High Rainfall	> 35 mm rain	S6-06 Clause 1.8.2.3 – Drainage systems – deck drainage required for 1/10 year storm S6-06 Clauses 6.4 and 6.5 - Foundation design and Geotechnical investigation – consider groundwater effects, slope stability, erosion	
9	Sustained Rainfall	≥ 5 consecutive days with > 3.5 mm rain		
10	Longer Sustained Rainfall	≥ 23 consecutive days with > 10 mm rain		Eliminated from the Assessment at the Workshop. Not relevant for this infrastructure assessment.

Figure 2.4: Climate Parameters and Infrastructure Indicators Selected for the Risk Assessment

#	Climate Parameter	Infrastructure Indicator	Source	Comments
11	Low Rainfall	≥ 10 consecutive days with precipitation < 0.2 mm		Eliminated from the Assessment at the Workshop. Not relevant for this infrastructure assessment.
12	Prolonged Dry Periods (Drought)	≥ 112 consecutive days with precipitation < 0.2 mm		Eliminated from the Assessment at the Workshop. Not relevant for this infrastructure assessment.
13	Snow (Frequency)	Days with snow fall > 10 cm		
14	Snow Accumulation	5 or more consecutive days with a snow depth > 60 cm	S6-06 Clause 3.1 – Snow loads not normally considered on bridges because a considerable snow load will cause a compensating reduction in traffic load. S6-06 Clause 12.4.1 – consider snow accumulation and snow removal from the deck when considering bridge barrier systems. Maintenance Response Standards.	Eliminated from the Assessment at the Workshop. Not relevant for this infrastructure assessment.
15	Snow Storm / Blizzard	8 or more days with blowing snow	S6-06 Clause 3.1 – Snow loads not normally considered on bridges because a considerable snow load will cause a compensating reduction in traffic load. S6-06 Clause 12.4.1 – consider snow	

Figure 2.4: Climate Parameters and Infrastructure Indicators Selected for the Risk Assessment

#	Climate Parameter	Infrastructure Indicator	Source	Comments
			accumulation and snow removal from the deck when considering bridge barrier systems. Maintenance Response Standards.	
16	Rain / Snow / Wind	Rain on snow including temperature and wind speed		Eliminated from the Assessment at the Workshop. Not relevant for this infrastructure assessment.
17	Rain on Snow	Period where rain falls on existing snowpack.	S6-06 Clause 1.1.1 – Scope of code – for structures subject to avalanche retain specialists to review and advice. S6-06 Clauses 6.4 and 6.5 - Foundation design and Geotechnical investigation – consider groundwater effects, slope stability, erosion	
18	Hail / Sleet	Days with precipitation falling as ice particles		
19	Rain on Frozen Ground	Precipitation > 6 mm/3h No snowfall, Surface Temperature $< 0\ ^oC$		
20	Freezing Rain	9 or more days with rain that falls as liquid and freezes on contact	S6-06 Clause 3.12.6 – Ice Accretion – design for ice accretion effects	Eliminated from the Assessment at the Workshop. Addressed under Climate Parameter 19.
21	Visibility	$\geq$ 15 hours per year with visibility $<$ 1,000 m		Not evaluated due to lack of good modeling information.

Figure 2.4: Climate Parameters and Infrastructure Indicators Selected for the Risk Assessment

#	Climate Parameter	Infrastructure Indicator	Source	Comments
				Accident reports indicate that this is a relevant parameter for highway safety. Candidate for additional study beyond this assessment.
22	High Wind / Downburst	≥ 8 days with Max winds ≥ 63 km/hr		
23	Rapid Snow Melt	Snow melt > 9 mm/3h		
24	Snow Driven Peak Flow Events	N/A		
25	Ice / Ice Jams	N/A		
26	Ground Freezing	Number of days below -5 ^{o} C		

2.3 Identify the Time Frame

The team identified two time horizons for the assessment:

- To the year 2050; and
- To the year 2100.

This was based on the notional functional service life of the highway without significant rehabilitation work.

2.4 Identify the Geography

The Yellowhead Highway runs from the eastern border with Alberta west through the Cariboo Mountains to Prince George, and through the Fraser Plateau, the Bulkley River Valley and the Skeena River Valley, before reaching the west coast at Prince Rupert.

There are several geographic features in the region that may have a bearing on the vulnerability assessment. These include:

- The Fraser Lakes;
- The Nechako River, which is dam controlled; and
- The Kenney Dam.

There is no significant climatological gradient in the region of the study, the area being generally in a plateau with no major gradients within the study area.

2.5 *Identify Jurisdictional Considerations*

The team identified a long list of potential jurisdictional interests either directly related to the highway and its corridor and also with the region in general. These interests are identified in **Figure 2.6**.

While maintaining an awareness of these interests and discussing the implications of climate change on the highway in the context of these interests, ultimately the team did not identify a jurisdictional interest that had any incremental affect on the highway when climate change factors were taken into consideration.

These interests were discussed extensively during the working meetings of the team and were considered during the two-day risk assessment workshop. However, ultimately the team did not identify a jurisdictional consideration that was materially affected by climate change.

Figure 2.5: Jurisdictional Considerations

Jurisdiction	Consideration
Department of Fisheries and Oceans	*Fisheries Act* requirements will influence the design of replacement structures on fish streams.
Ministry of Environment	• Wildlife and Vegetation • Fish habitat • Water Act Approvals • Biodiversity protection (e.g. fish, vegetation, wildlife, habitat) • Water Act approvals (e.g. diversions, withdrawals) • Pollution prevention (e.g. spills, contaminated runoff) • Parks and protected areas

Figure 2.5: Jurisdictional Considerations

Jurisdiction	Consideration
	• Provincial Park at Falls Lake • Etc.
Rail	
First Nations	There are no reserves along this section of the highway.
Ministry of Forests	Forest road access may be a concern.
Transport Canada	*Navigable Waters Protection Act* requirements will influence the design of replacement structures.
Industry Canada	Regulates Radio and Electronics as well as Explosive use
Pipelines (NEB) Natural gas etc.	May have some influence on maintenance and refurbishment
Power Transmission Lines	
Bulkley-Nechako Regional District	
Provincial Ministry of Environment Parks & Recreation	• BC Wildlife Act • BC Water Act

2.6 *Site Visit*

The team did not deem it necessary to conduct a site visit for this assessment.

The team comprised BC MoTI staff with significant hands-on experience in the design, operation, and maintenance of this highway. Thus, during the workshops the team had a deep foundation of skills and experience to draw from in assessing the impact of climate change on the infrastructure.

2.7 *Assess Data Sufficiency*

Upon completion of Step 1 of the Protocol, the team determined that they had sufficient data to proceed to Step 2 of the assessment.

In general, the experience of the team compensated for any lack of specific design data.

In retrospect, the team was correct in stating that there is sufficient data to actually assess the risk of climate change on infrastructure and accommodate most of the data gaps through experience and local knowledge.

Ultimately, two of the climate parameters were identified as areas of poor data sufficiency. These were:

- High Wind / Downburst; and
- Visibility

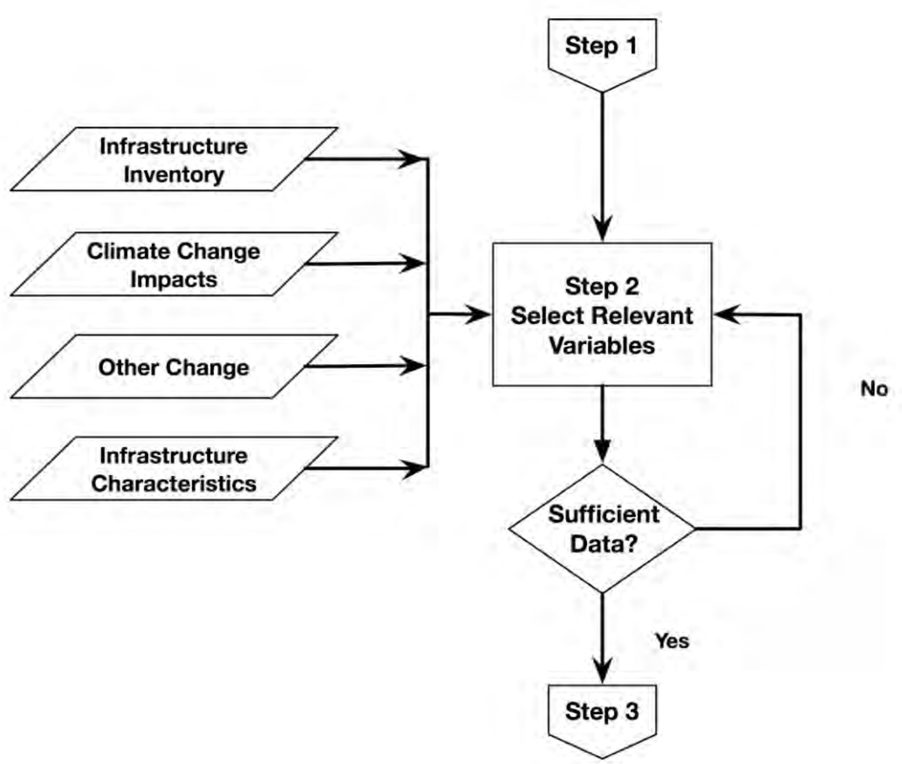
In both cases the team was unable to identify processes to backfill or augment the lack of information. However, the team remained concerned about the impact of these climate parameters on the serviceability of the highway and concluded that further work, outside of the context of the current study, is necessary to provide better resolution of these factors.

3 Step 2 – Data Gathering and Sufficiency

The Protocol applies a recursive process to identify, locate and define data used in the risk assessment process. In Step 1, the Protocol establishes the project boundary conditions. In Step 2, these definitions are further refined to provide an in-depth definition of the climate parameters and specific infrastructure sub-components to be considered in the risk assessment. This is accomplished through a detailed review of the specific characteristics of the infrastructure and its sub-components. Infrastructure components are the physical, operational and procedural features of the infrastructure that the team defines to be potentially vulnerable to climate change. Throughout the remainder of the assessment process, these components are reviewed, refined and assessed to determine the specific level of vulnerability. It is quite common that the process identifies no vulnerability for a large number of components. This is a positive outcome since it represents a focussed review of the situation and an active decision regarding vulnerability.

The process followed the steps identified in the process flowchart presented in **Figure 3.1**.

Figure 3.1: Step 2 – Data Gathering and Sufficiency Process Flowchart



For the purposes of this section of this report, we provide the incremental or refined information that was generated through Step 2 of the process. Where no change arose in the data being used, we refer the reader to the appropriate part of Section 2 of this report.

The team undertook the analysis required for Step 2 over approximately eight weeks between late November 2010 and mid January 2011. The work was initiated at a teleconference with the project team on November 22, 2010 and was ongoing through the end of the Workshop in Prince George, B.C. on January 18 – 19, 2011.

The complete Step 2 Worksheet for the assessment is presented in **Appendix D**.

3.1 *State Infrastructure Components*

The team spent considerable effort to define relevant infrastructure components for the Yellowhead Highway. As noted above, the team continuously refined this list throughout the process and finalized the list at the risk assessment workshop in mid January 2011. We found this ongoing review and refinement to be very beneficial.

The team reviewed each component of the infrastructure and considered its vulnerability from a number of perspectives, based on the experience and skills represented by the team membership. This allowed the team to conduct a thorough review and ensured that, at the risk assessment workshop, there was a common understanding of the infrastructure characteristics being contemplated in the assessment.

The final infrastructure component listing is presented in **Figure 3.2**.

Figure 3.2: Infrastructure Component Listing

	Above Ground
1	Asphalt - Hot in Place
2	Asphalt - Seal Coat
3	Pavement Marking
4	Shoulders (Including Gravel)
5	Barriers
6	Curb - Concrete
7	Curb - Asphalt
8	Luminaires
9	Poles
10	Signs - Sheeting
11	Signs - Wood or metal bases
12	Signage - Side Mounted - Over 3.2 m^2

Figure 3.2: Infrastructure Component Listing

13	Signage - Overhead Guide Signs
14	Overhead Changeable Message Signs – Weigh Scale
15	Ditches
16	Embankments/Cuts
17	Natural Hillsides
18	Engineered Stabilization Works
19	Structures that Cross Streams - Bridges
20	Structures that Cross Roads - Bridges
21	Railways (Drainage Interaction)
22	River Training Works - Rip Rap
23	Retaining Walls - MSE Walls
24	Asphalt Spillway and Associated Piping – Above Ground Elements
Below Ground	
25	Pavement Structure
26	Catch Basins
27	Roadway Drainage Appliances
28	Sub-Drains
29	Below Ground Third Party Utilities
30	Above Ground Third Party Utilities
31	Culverts < 3m in diameter
32	Culverts ≥ 3m in diameter
33	Piping/Culvert - Below Ground Elements.
Miscellaneous	
35	Winter Maintenance
36	Habitat Features
37	Routine Maintenance
38	Pavement Marking Repair
39	Pavement / Curb/ Barrier / Sign Repair

3.2 *Detailed Climate Considerations*

Two approaches were used to establish the climate parameters used in the climate change risk assessment:

1. Climate modeling; and
2. Sensitivity analysis.

Although climate modeling was a good tool for establishing both the baseline and future climates, the team did identify a number of infrastructure-specific climate parameters that were not amenable to modeling analysis, at least within the timeframe of the assessment.

Parameters that could not be determined using modeling were assessed sensitivity analysis. This process involves arbitrarily assigning climate change probabilities for specific parameters and then adjusting those probabilities using sensitivity analysis to determine the impact on risk outcomes.

Both of these approaches are sanctioned by the Protocol.

As discussed in **Section 2.7**, the team identified two climate parameters to be unnameable to any of the three approaches and recommended that further studies be conducted to resolve these parameters.

In the following sections we describe the detailed processes used to establish climate change parameters used in the assessment.

3.3 *Climate Modeling*

3.3.1 Global Circulation and Regional Climate Models

A general circulation model (GCM), also known as a global climate model, is a computer model of the general circulation of planetary atmosphere and oceans based on fundamental thermodynamic principles. Climate scientists use these models to predict changes in climatic conditions over extended periods.

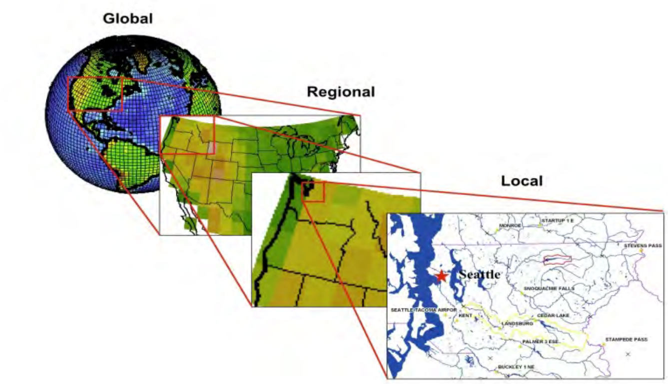
GCMs calculate very complex thermodynamic relationships across the globe based on a theoretical segmentation of the atmosphere into rectangular boxes and quantifying the mass and energy balances across the box's boundaries.

Regional climate models (RCMs) use similar principles of conservation of energy, mass and momentum to generate finer regional representation of climate. Developed using the same physical principles as GCMs, RCMs concentrate on a portion of the globe and allow simulations at higher spatial resolution.

RCMs obtain their boundary conditions from GCMs. Typically, GCMs have a horizontal resolution of 250 km and a vertical resolution of 1 km. RCMs have a horizontal resolution of 50 km, often called a 50 km x 50 km grid. As a consequence, there is a scale mismatch between the

RCMs and local climatic conditions. RCMs predict average conditions across the grid and not localized climate events. **Figure 3.3** gives a sense of this scale mismatch.

Figure 3.3: Scale Mismatch between, Global/Regional Climate Models and Local Conditions



3.3.2 Climate Modeling Output

The Pacific Climate Impacts Consortium (PCIC) provided climate modeling for the study. PCIC's summary report is presented in **Appendix E**.

PCIC used five GCMs to project future global climatic conditions, and five RCMs to obtain regional estimates for the area of the Yellowhead Highway. The RCM/GCM parings used in this study are the:

1. Canadian Regional Climate Model (CRCM)
   - Driven by the Third Generation Global Coupled Climate Model (CGCM3)

2. Hadley Centre Regional Climate Model (HRM3)
   - Driven by the Hadley Centre Coupled Model, Version 3 (HadCM3)

3. ICTP Regional Climate Model (RCM3)
   - Driven by the Geophysical Fluid Dynamics Laboratory Global Climate Model (GFDL)

4. ICTP Regional Climate Model (RCM3)
   - Driven by the Third Generation Global Coupled Climate Model (CGCM3)

5. Iowa State University MM5 – PSU/NCAR Mesoscale Model (MM5I)

- Driven by National Centre for Atmospheric Research - Community Climate System Model (CCSM)

6. Weather Research and Forecasting Model (WRFG)
   - Driven by National Centre for Atmospheric Research - Community Climate System Model (CCSM)

For this study PCIC selected all RCM grid cells that intersected the highway over the length of the study area.

GCMs are based on assumed greenhouse gas emission scenarios, developed by the Intergovernmental Panel on Climate Change (IPCC). For the purposes of this study, PCIC used the following emissions scenarios.

20C3M (Present)

Greenhouse gases evolving as observed through the 20th Century

A2

Represents a very heterogeneous world. The underlying theme is that of strengthening regional cultural identities, with and emphasis on family values and local traditions, high population growth, and less concern for rapid economic development. This scenario generally assumes:

- Independently operating, self-reliant nations;
- Continuously increasing population;
- Regionally oriented economic development; and
- Slower and more fragmented technological changes and improvements to per capita income.

A1B

Represents a future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technology. Major underlying themes are:

- A more integrated world;
- Rapid economic growth;
- A global population that reaches 9 billion in 2050 and then gradually declines;
- The quick spread of new and efficient technologies;
- A convergent world - income and way of life converge between regions. Extensive social and cultural interactions worldwide; and
- A balanced emphasis on all energy sources.

PCIC estimated climate averages for present and future projections. The specified time periods were:

- Present climate - 1971 to 2000;
- Medium-term future (mid-century) - 2041 to 2070 (short: 2050s); and
- Long-term future (late-century) - 2085 to 2115 (short: 2100s).

For the RCM based results only the 2050s were available.

GCMs that apply A2 cover the mid range to high range of climate change forecasts. Thus, these models provide a reasonable range of future climate scenarios without assuming the extreme worst case conditions inherent in the A1FI emissions scenario where there is a high reliance on fossil fuel use world-wide.

GCMs that apply A1B cover the mid range to high range of climate change forecasts assuming a change in technology away from fossil fuels over the longer term. Thus, these models provide a reasonable range of future climate scenarios with a somewhat more optimistic longer-range outlook.

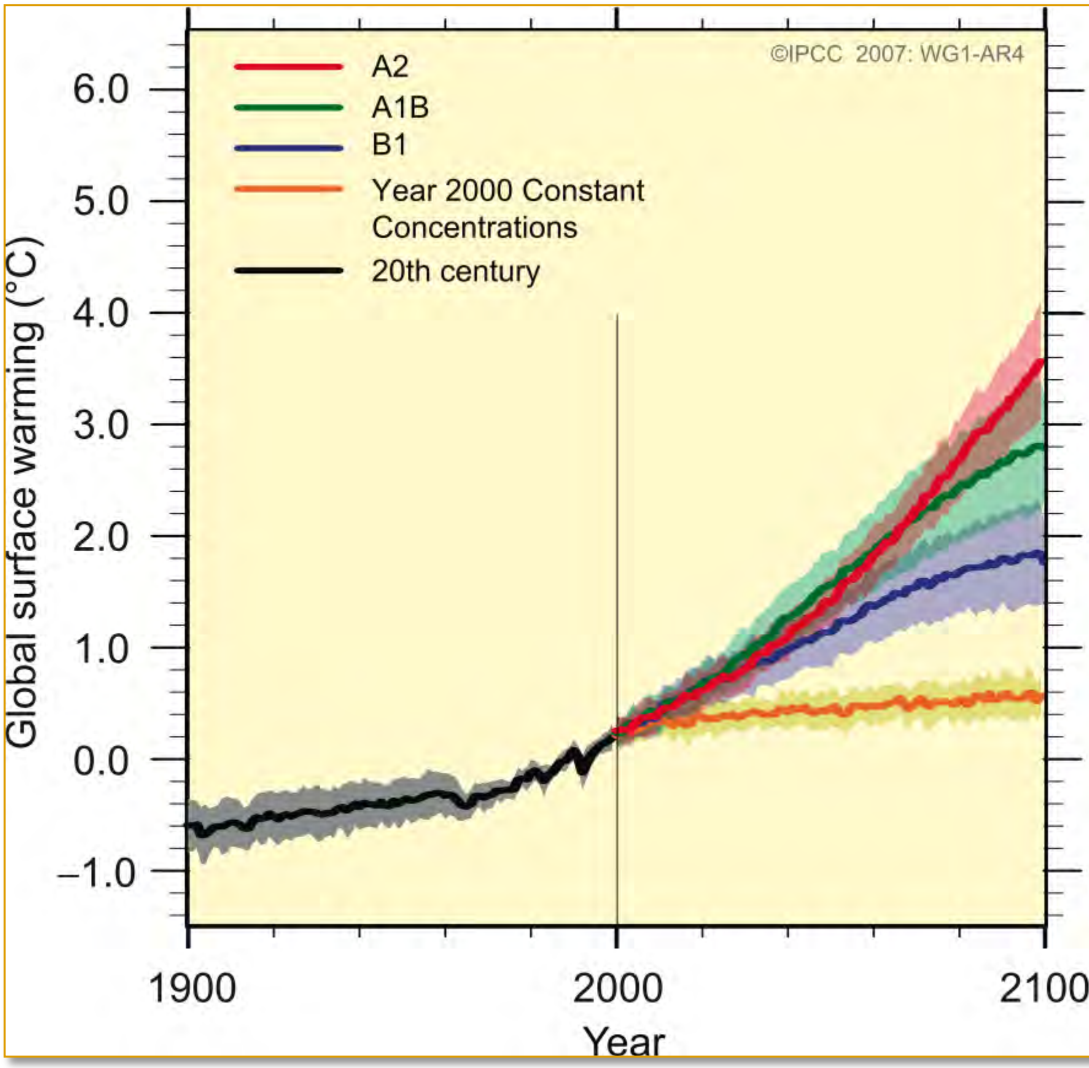
RCMs will yield a range of values depending on the imbedded climate assumptions, thermodynamic models and calculation methodologies. Thus, in climate change work it is normal to use an ensemble of model outputs to cover a range of conditions and provide more statistical certainty. For this study PCIC applied the models outlined above.

Figure 3.4 presents the range of future climate temperature forecasts driven by the various IPCC emission scenarios and GCMs. The range of forecast global climate conditions as well as the range of model outputs is clearly outlined by the colored bands on the right side of the figure.

A2, represented by| the red line and pink shaded region of the graph, covers between mid-range to the upper quartile of all forecasts. As the model forecast advances closer to the year 2010, A2 is much more representative of the higher boundary conditions.

A1B, represented by the green line and green shaded area, covers the mid-range to upper quartile of all forecasts over the medium-term. However, over the longer horizon the forecast tapers off and covers more mid-range to three quarters of the upper range of forecasts.

Figure 3.4: Range of Future Climate Forecasts based on Different IPCC Emission Scenarios



To compensate for scale mismatch, PCIC used statistical downscaling to tailor the RCM outputs to local conditions in the Vanderhoof region. The approach involves:

- Evaluation of present climate statistics from historic station records;
- Synoptic analysis of larger scale weather systems and how they affect local conditions; and
- Statistical (regression) analysis.

PCIC also reviewed historic weather conditions in the region through weather data retrieved from Environment Canada weather satiations dispersed throughout the region. The location of the weather stations used for the study is identified in **Figure 3.5**.

PCIC used the historic (baseline) conditions to rationalize results from the RCMs so that there is a meaningful correlation between observed and predicted climatic conditions in the study area.

For this study, PCIC used the 27 (+2) core climate change indices, known as the Climdex indices. The definitions of these indices are shown in **Figure 3.6**. Despite some overlap, the Climdex indices must not be confused with the climate parameters of Figure 2.4, which forms the basis of the risk assessment.

In order to evaluate the results from the models, PCIC applied two different analytical procedures to the modeling and meteorological information:

- Probabilistic Analysis, and
- Statistical Downscaling.

In addition, PCIC provided return period analysis for precipitation, high temperature and low temperature based on both the A1B and A2 climate change scenarios. This analysis is presented in Section 3.3.5.

PCIC provides detailed descriptions of these analytical processes in their report, presented in **Appendix E**.

Figure 3.5: Location of Weather Stations used in the Study

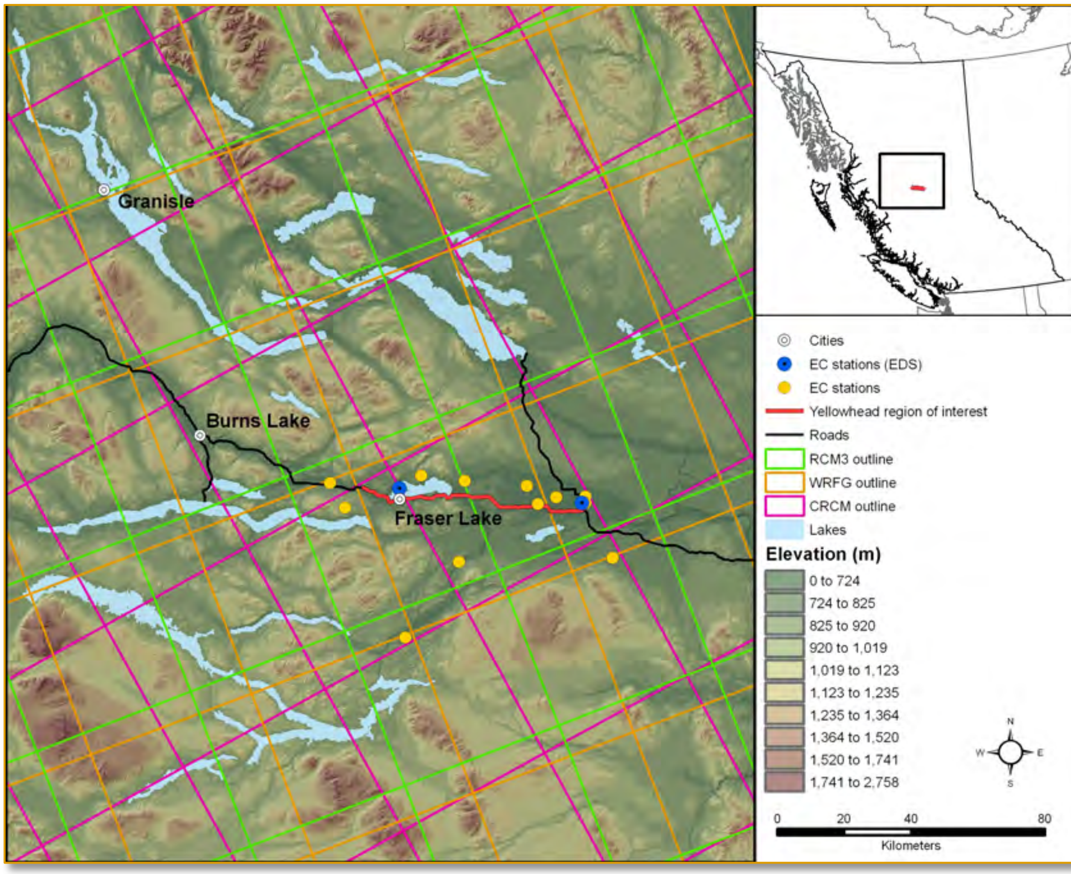


Figure 3.6: Definitions for Extreme Climate Events (Climdex)

Indicator name	Definitions	Units
Consecutive dry days	Maximum number of consecutive days with RR<1mm	Days
Cold spell duration	Days with at least 6 consecutive days when $TN<Q_{10}$	Days
Consecutive wet days	Maximum number of consecutive days with RR>=1mm	Days
Diurnal T range	Monthly mean difference between TX and TN	ºC
Frost days	Annual count when TN(daily minimum)<0ºC	Days
Growing season Length	Days between first and last span of at least 6 warm enough days	Days
Ice days	Annual count when TX(daily maximum)<0ºC	Days
Annual total wet-day precipitation	Annual total PRCP in wet days (RR>=1mm)	mm
Number of heavy precipitation days	Annual count of days when PRCP>=10mm	Days

Figure 3.6: Definitions for Extreme Climate Events (Climdex)

Indicator name	Definitions	Units
Number of very heavy precipitation days	Annual count of days when PRCP>=20mm	Days
Very wet days	Annual total PRCP when RR>95th percentile	mm
Extremely wet days	Annual total PRCP when RR>99th percentile	mm
Number of days above nn mm	Days when PRCP>=nn mm, nn is user defined threshold	Days
Max 1-day precipitation	Monthly maximum 1-day precipitation	mm
Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
Simple daily intensity index	Annual total precipitation divided by the number of wet days (PRCP>=1.0mm)	mm
Summer days	Annual count when TX(daily maximum)>25ºC	Days
Cool nights	Percentage of days when TN<10th percentile	Days
Median Tmin	Percentage of days when TN>50th percentile	Days
Warm nights	Percentage of days when TN>90th percentile	Days
Min Tmin	Monthly minimum value of daily minimum temp	ºC
Max Tmin	Monthly maximum value of daily minimum temp	ºC
Tropical nights	Annual count when TN(daily minimum)>20ºC	Days
Cool days	Percentage of days when TX<10th percentile	Days
Median Tmax	Percentage of days when TX>50th percentile	Days
Warm days	Percentage of days when TX>90th percentile	Days
Min Tmax	Monthly minimum value of daily maximum temp	ºC
Max Tmax	Monthly maximum value of daily maximum temp	ºC
Warm spell duration	Days with at least 6 consecutive days when $TX>Q_{90}$	Days

3.3.3 Results from Probabilistic Analysis

One of the key outputs from PCIC's work was a probabilistic analysis of the likelihood of these extreme climatic events in both the baseline climate and in the future climate, as predicted by the RCMs. In order to generate meaningful results, especially for predicted probability of specific climatic events, PCIC made a number of small adjustments to the climate parameter list identified by the project team. These adjustments had no material impact on the study considerations but allowed PCIC to generate statistically meaningful values. As this work was based on RCM outputs, projections are provided only for the 2050 time horizon.

Each model was run for two grid cells covering the Yellowhead region. The results from this analysis for the medium-term future (2041 – 2070) are presented in **Figure 3.7**.

Figure 3.7: Event Probabilities per Year for Medium-Term Future (2041 to 2070)

	High Temperature	Low Temperature	Extreme Rainfall	Ground Freeze	Snow Accumulation
Observed 1971-2000	0.07	**4.59**	**0.08**	**39.82**	**0.23**
CGCM3/CRCM					
Grid Cell 1	0.00	1.58	0.67	24.00	0.09
Grid Cell 2	0.00	1.64	0.67	24.37	0.09
CGCM3/RCM3					
Grid Cell 1	0.15	1.18	0.18	25.85	
Grid Cell 2	0.12	1.33	0.52	25.39	
GFDL/RCM3					
Grid Cell 1	1.55	0.85	0.12	27.46	
Grid Cell 2	1.70	0.85	0.18	27.12	
HADCM3/HRM3					
Grid Cell 1	1.67	0.21	0.06	25.94	
Grid Cell 2	1.88	0.00	0.03	25.88	
CCSM/MM5I					
Grid Cell 1	0.00	0.33	0.12	23.46	
Grid Cell 2	0.00	0.33	0.15	24.00	
CCSM/WRFG					
Grid Cell 1	0.03	0.52	0.18	26.68	
Grid Cell 2	0.15	0.49	0.33	26.68	

3.3.4 Results from Statistical Downscaling

Statistical downscaling was based on both the 2050 and 2100 time horizons.

The results from the statistical downscaling work can be summarized, as follows.

- The number of frost days will decline sharply from about 200 to approximately 150 by the year 2100
- The number of ice days will decrease.

- The growing season length will increase from roughly 170 days to nearly 200 days by the end of the century.
- Precipitation totals may increase from 500 mm to about 600 mm.
- There will be more extreme weather events, overall.
- The portion of days where the maximum temperature is above the present-day median will increase from 50% to almost 80% by the end of the century

- The annual minimum temperature will increase from -25°C to -20°C by 2100.
- Annual maximum temperature values, which are presently safely below the 35°C mark relevant to bridge and highway design, will start to cross this line by mid century and even approach and exceed 40°C by the end of the century.

3.3.5 Return Period Analysis

Another key output from PCIC's work, was a forecast of return periods for precipitation, high temperature and low temperature based on both the A1B and A2 climate change scenarios. This work was used both in the Step 3 – Risk Assessment and Step 4 – Engineering Analysis. The results of the return period analysis are presented in **Figure 3.8**.

Figure 3.8: Present and Future Return Values for Precipitation, High Temperature and Low Temperature

	Present		Future A1B		Future A2	
	Observed	20C	2050s	2100s	2050s	2100s
Precipitation (mm/d)						
5y	30	23	25	28	28	37
10y	35	26	28	33	32	44
25y	41	30	32	38	38	53
50y	45	33	35	42	42	59
100y	50	36	37	45	46	66
200y	54	39	40	49	50	72
High Temperature (°C)						
5y	34	34	35	36	35	37
10y	35	36	37	38	36	39
25y	36	38	39	39	38	41
50y	37	39	41	41	39	43
100y	38	40	42	42	40	44
200y	39	42	44	43	41	46

Figure 3.8: Present and Future Return Values for Precipitation, High Temperature and Low Temperature

Low Temperature (°C)	Present		Future A1B		Future A2	
	Observed	20C	2050s	2100s	2050s	2100s
5y	-42	-40	-37	-33	-38	-34
10y	-46	-43	-40	-36	-42	-37
25y	-51	-47	-45	-39	-46	-41
50y	-55	-50	-48	-42	-49	-45
100y	-58	-53	-51	-45	-52	-48
200y	-62	-56	-54	-47	-55	-51

3.3.6 Climate Modeling Uncertainties

Climate modeling is based on inherent assumptions regarding likely emissions scenarios. Additionally, there is a significant level of uncertainty associated with both the modeling and the analytical approaches used to downscale the information generated by the regional climate models to local conditions. PCIC addressed this concern by correlating model predictions with observed, baseline, climate conditions.

Socio-economic scenarios drive both RCMs and GCMs. As in any economic forecast, there is an imbedded level of speculation and uncertainty associated with these scenarios. The impact of these uncertainties is a range of outputs from the various scenarios and models. As stated in **Section 3.3.2**, PCIC addressed this issue by providing output from an ensemble of models.

Climate models are based on very precise thermodynamic calculations. However, the outputs from these models are only as accurate as the input assumptions. Since, there may be a relatively high degree of uncertainty associated with the imbedded assumptions, there can be a high level of uncertainty associated with the model outputs.

To compensate for this uncertainty, where possible, PCIC ground-tested the data by correlating model outputs with observed meteorological data. Nonetheless, users of climate model data must routinely address a range of model outputs and confidence intervals. This is normally achieved through testing the model output against local knowledge and broader synoptic analysis.

3.3.7 Climate Modeling Gaps

Based on the project schedule and limitations in climate modeling, PCIC was unable to provide model-based projections for the following climate parameters:

- Climate Parameter 20, Freezing Rain
- Climate Parameter 21, Visibility

Visibility was removed from the study due to lack of climate modeling information. Visibility is a significant concern with respect to highway / traffic safety issues. Police accident reports suggest a correlation between visibility and traffic accidents. However, it is very difficult to resolve fog or other visibility issues from the meteorological record or from climate modeling information. Given this outcome, BC MoTI should consider additional studies on the impact of climate change on potential visibility issues.

3.4 *Sensitivity Analysis*

3.4.1 Description of Analysis

Sensitivity analysis was conducted for three Climate Parameters:

- Climate Parameter 19, Rain on Frozen Ground
- Climate Parameter 25, Ice / Ice Jams
- Climate Parameter 26, Ground Freezing

In the absence of synoptic or climate model data, the team arbitrarily assigned a probability score of "3" to Climate Parameter 19 and Climate Parameter 25, indicating that it is moderate or probable that, over the study period, this parameter will change. Based on these scores, the team completed the risk assessment, described in **Section 4**. Once this work was complete, we arbitrarily increased the probability score to "4" indicating that the parameter will change such that it often occurs over the study period. Based on this change we reassessed the resulting risk profiles.

Based on the precipitation, snowfall and frost information provided by PCIC, the initial probably score of "3" is rational.

Since this analysis is subjective, it is important to test the assumptions by increasing the scoring to generate higher risk outcomes from the assessment. Once this is done, the team can assess the impact of the probability scoring and make rational recommendations regarding the need for additional work to further resolve these climate parameters.

For Climate Parameter 26, the sensitivity analysis involved decreasing the severity score from "2" to "1". Based on input from PCIC, and the professional judgment of the team, climate change in this region should result in relatively beneficial impacts on ground freezing. That is, the temperature is increasing and this will result in shorter periods of frozen ground. At the workshop the team assessed the severity of this event as very minor, a value of "2" based on their understanding of the improvement that will likely occur. However, the event is given a relatively high probability of "6". Thus the original scoring suggested that this might still represent a moderate level of risk to asphalt. We tested this assumption by slightly reducing the severity score to a value of "1". The impact of this sensitivity was to dramatically reduce the risk profile of these events with respect to asphalt.

3.4.2 Sensitivity Analysis Gaps

Sensitivity analysis is subjective. Probability scores are assigned arbitrarily and then tested by adjusting the scores. The results are also rationalized through the skills and experience of the assessment team. Sensitivity analysis is not the best approach for assessing risk. However, it does allow the team to screen risks and determine where more detailed study may be necessary.

3.5 *State the Timeframe*

The team did not adjust the timeframe based on their deliberations in Step 2. The assessment timeframe is described in **Section 2.3**.

3.6 *State the Geography*

The team did not adjust the geographical definition based on their deliberations in Step 2. The assessment geography is described in **Section 2.4**.

3.7 *State Specific Jurisdictional Considerations*

The team did not adjust the jurisdictional considerations based on their deliberations in Step 2. The jurisdictional considerations are described in **Section 2.5**.

3.8 *State Other Potential Changes that Affect the Infrastructure*

The team identified three situations that fire history, including things that affect fire history such as Mountain Pine Beetle, could result in outcomes that may adversely affect the infrastructure.

Fire history can have an affect on the drainage characteristics of the watershed and exacerbate highway drainage, erosion, slope stability and debris torrent concerns. The team discussed these factors at the workshop but determined that the potential impacts were beyond the scope of this assessment. Nonetheless, the team identified that these issues should not be neglected and that other studies should consider these impacts. Ultimately, these issues have minimal direct impact on highway design and operational practices, other than drainage considerations.

3.9 *Site Visit to the Yellowhead Highway*

As stated in **Section 2.6** the team did not conduct site visits as part of this assessment.

3.10 Assess Data Sufficiency

There is some uncertainty associated with establishing future climatic conditions. The team used two approaches to establish future climate conditions. Each approach contained inherent uncertainties that were addressed by the team. For all but one of the climate parameters, the team deemed that the available climate data was sufficient to conduct the risk assessment. However, for Climate Parameter 21, Visibility, the team deemed that there was insufficient data to proceed to risk assessment. The rationale for this decision is outlined in the following section.

3.10.1 Visibility

Climate Parameter 21, Visibility, was removed from the study due to lack of climate modeling information. Visibility is a significant concern with respect to highway / traffic safety issues. Police accident reports suggest a correlation between visibility and traffic accidents. However, it is very difficult to resolve fog or other visibility issues from the meteorological record or from climate modeling information.

Fog requires moisture to form. However, there are multiple causes of fog, including:

- Very localized, from warm air over snow;
- Valley fog; or
- Low clouds.

In addition, visibility issues also arise in other weather related conditions, including blowing snow or smoke blown into the region from forest or brush fires.

The team determined that this issue requires more study to define how visibility issues arise currently on the highway.

Given this outcome, BC MoTI should consider additional studies on the impact of climate change on potential visibility issues.

4 Step 3 – Risk Assessment

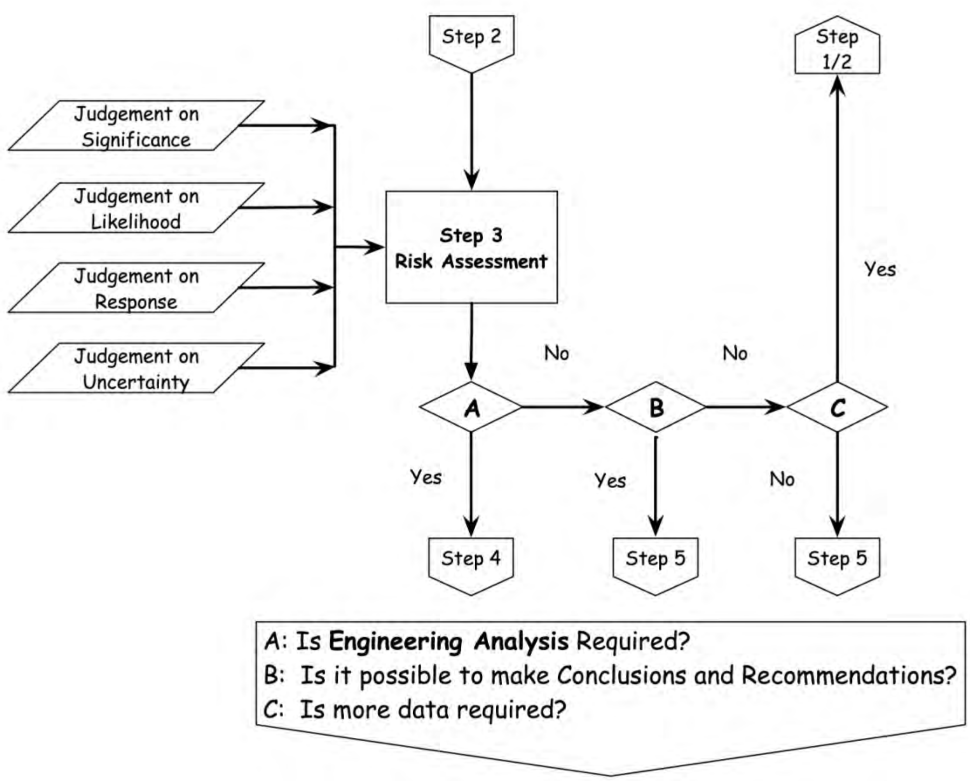
In this step the team identified the infrastructure's response to climate events. The protocol directed the team to develop:

- A list of relevant climate events; and
- A list of relevant infrastructure components.

Using a spreadsheet, the team examined interactions between infrastructure and climatic events that, potentially, could lead to vulnerability. Pairings between infrastructure components and climate events are called interactions.

The process flowchart for Step 3 of the protocol is presented in **Figure 4.1**.

Figure 4.1: Step 3 – Risk Assessment Process Flowchart



4.1 *Consultation with Owner and Operations Personnel*

BC MoTI drove the climate change risk assessment. Nodelcorp provided facilitation services and technical advice. Consequently, the project demanded a significant amount of consultation within the BC MoTI team and with PCIC to ensure that sufficient data was identified and defined to effectively conduct the two-day risk assessment workshop that formed the focus of this project. **Figure 4.2** outlines the team's deliberation process from November 2010 through February 2011.

Figure 4.2: Consultation Process

Date	Participants	Purpose
Nov 9	BC MoTI Team	Completed Worksheet 1
Nov 10	BC MoTI Sub Group	Evaluated and Discussed Relationship Between Collision Data and Visibility
Nov 22	BC MoTI Team	Completed Worksheet 2
Dec 8	BC MoTI Team	**Table Top Session** **Performance Response** **Y/N** Analysis
Jan 5	BC MoTI Team	**Table Top Session (Contd.)** **Performance Response** **Y/N** Analysis
Jan 11	Climate Parameter Sub Group	Review of Probability Scoring for Climate Parameters
Jan 18-19	BC MoTI Team - PCIC	**Workshop** Complete Risk Assessment

4.1.1 Risk Assessment Workshop

As outlined above, the Risk Assessment workshop was conducted over a two-day period on January 18 and 19, 2011. The team used this workshop to carry out the analysis defined by Step 3 of the Protocol. At the completion of the workshop the team had resolved the climate change risk profile for the Yellowhead highway and had identified several parameters for Step 4 – Engineering Analysis.

A list of workshop participants is presented in **Appendix J**.

4.1.2 Owner's Risk Tolerance Thresholds

The Protocol directs the practitioner to confirm the infrastructure owner's risk tolerance thresholds prior to conducting the risk assessment. The Protocol suggests High, Medium and Low risk thresholds. On January 13, 2010, BC MoTI confirmed their acceptance of the risk thresholds defined by the Protocol for application in this process.

Figure 4.3 outlines the risk thresholds used for this risk assessment.

Figure 4.3: Risk Tolerance Thresholds

Risk Range[1]	Threshold	Response
< 12	Low Risk	• No immediate action necessary
12 – 36	Medium Risk	• Action may be required • Engineering analysis may be required
> 36	High Risk	• Immediate action required

4.2 Risk Assessment Methodology

Based on the Protocol, the team developed a risk value for each of the climate-infrastructure interactions identified through Step 1 and 2 of the assessment. The Protocol defines a default risk assessment process is based on scales of 0 to 7**.** For each interaction, the team:

- Established the probability of the climate parameter changing during the time horizons of the assessment;
    - Using a scale of 0 to 7, where:
        - 0 means that the parameter will not change in the timeframe of the assessment; and
        - 7 means certainty that the parameter will change in the timeframe of the assessment; and
- Established a severity resulting from the interaction;
    - Using a scale of 0 to 7, where
        - 0 means no negative consequences in the event that the interaction occurs; and
        - 7 means a significant failure will result if the interaction occurs.

Based on the protocol, the team selected the scale definitions for probability and severity that were applied consistently through the risk assessment process. **Figure 4.4** presents the

[1] Risk scores range from 0 to 49 based on the 0-7 probability and severity scales used in the assessment.

probability scaling definitions that were applied by the team. **Figure 4.5** presents the severity definitions. These tables were extracted from the Protocol. The team applied the highlighted definitions. Alternative definitions, offered by the Protocol, are de-emphasized in the figures.

Figure 4.4: Probability Scale Factors

Scale	Probability*		
	Method A	Method B	Method C
0	negligible or not applicable	<0.1 % <0.1 / 20	negligible or not applicable
1	improbable / highly unlikely	5 % 1 / 20	improbable 1:1 000 000
2	remote	20 % 4 / 20	remote 1:100 000
3	occasional	35 % 7 / 20	occasional 1:10 000
4	moderate / possible	50 % 10 / 20	moderate 1:1 000
5	often	65 % 13 / 20	probable 1:100
6	probable	80 % 16 / 20	frequent 1:10
7	certain / highly probable	>95 % >19 / 20	continuous 1:1

Figure 4.5: Severity Scale Factors

Scale	Magnitude	Severity of Consequences and Effects
	Method D	Method E
0	no effect	negligible or not applicable
1	measurable 0.0125	very low / unlikely / rare / measurable change
2	minor 0.025	low / seldom / marginal / change in serviceability
3	moderate 0.050	occasional loss of some capability
4	major 0.100	moderate loss of some capacity
5	serious 0.200	likely regular / loss of capacity and loss of some function
6	hazardous 0.400	major / likely / critical / loss of function
7	catastrophic 0.800	extreme/ frequent/ continuous /loss of asset

Based on these probability and severity scales, the team calculated the climate change risk for each sub-component using the following equation:

$R = P \times S$

Where:

R = Risk
P = Probability that the climate parameter will change
S = Severity of the interaction

4.3 The Risk Assessment Spreadsheet

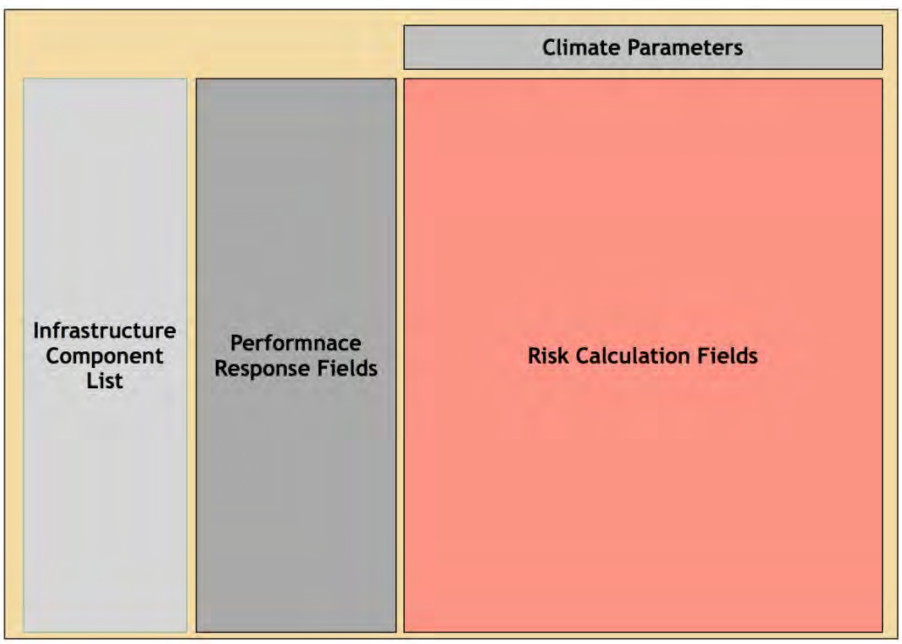
The team maintained a record of their deliberations in Worksheet 3 that is provided by PIEVC as a companion to the Protocol.

The workbook is split into four key areas:

- Columns
  - Each climate parameter has a dedicated column
- Rows
  - Each infrastructure element has a dedicated row
- Performance Response Fields:
  - Where the team identifies potential performance response characteristics for each infrastructure component
- Risk Calculation Fields:
  - Where the team notes probability and severity scores and calculations climate change risk profiles.

At first, the workbook can appear daunting. The spreadsheet is large and there is a lot of information compressed into a very small space. In the following sections we will provide a tour of the workbook and present the results that the team developed for the risk assessment. To help in this process, we have developed a legend for the workbook. The workbook legend is presented in **Figure 4.6**.

Figure 4.6: Worksheet 3 Legend



The completed Worksheet 3 is presented in **Appendix F**.

4.3.1 Spreadsheet Columns

The spreadsheet columns were used to document the climate parameters selected for the evaluation. The climate parameters developed in Section 2.2 were transferred to the title row for these columns.

Under the title row, each column was split into four sub-columns. For each climate parameter, the sub columns were used to document the results of the yes / no analysis, probability score, severity score and calculated risk for each climate-infrastructure interaction.

4.3.2 Spreadsheet Rows

The spreadsheet rows were used to document the infrastructure components selected for the evaluation. The infrastructure components developed in Section 3.1 were transferred to the title column for these rows.

4.4 Performance Response Analysis

The first step in assessing climate change risk is to identify the potential performance responses for each infrastructure component considered in the assessment.

In establishing conceivable performance responses the team considered the most likely response of each infrastructure component to contemplated climate events. This was based on the team's professional judgment and experience.

This analysis serves as a preliminary screening process. Any infrastructure component that exhibits no material performance response, in the judgment of the team, can be excluded from further assessment.

To aid in this assessment the team referred to the performance response listing provided in Appendix B of the protocol. During the teleconferences on December 8 and January 5 the team refined the list into a form more representative of the highway and the language and terminology used by the engineering, operation and maintenance personnel who actually work on the highway. This refinement facilitated discussion of potential infrastructure responses to the contemplated climate events and allowing for comprehensive and transparent discussions to occur within the team. The refined list is presented in **Figure 4.7**.

Figure 4.7: Performance Response Considerations

Performance Response Keyword	Potential Infrastructure Response
Infrastructure Design (bridge, pavement, etc.)	• Loss of load carrying capacity • Fatigue • Loss of serviceability • Deflection • Cracking and deterioration • Foundation design considerations

Functionality (capacity, reliability, serviceability)	• Reduced level of service, serviceability, reliability
	• Reduced effective capacity
	  o Short term
	  o Medium term
	  o Long term
	• Equipment - Component selection, design, process and capacity considerations

Drainage (watershed, surface/groundwater)	• Erosion along streams, rivers, and ditches • Erosion scour of associated or supporting earthworks • Sediment transport and sedimentation • Channel realignment / meandering • Change in water quantity • Slope stability
Maintenance (structure/materials changes)	• Structural aspects • Functionality & Effective Capacity • Materials Performance (changes over time from design expectation) • Pavement Aspects (i.e. hail, softening, cracking from freeze thaw and other causes)
Emergency Response	• Storm • Flood • Ice • Water damage
Policy / Guidelines / Engineering Standards	• Codes • Public sector policy

Figure 4.7: Performance Response Considerations

Performance Response Keyword	Potential Infrastructure Response
	• Land use planning documents Guidelines
Highway Safety	• Climate events that compromise highway safety • Speed reductions
Environmental Effect	• Climate events that result in: • Coincident contamination • Impacts wildlife • Impacts on habitats

The team conducted the performance response analysis during teleconferences on December 8 and January 5.

The team did not eliminate any climate parameters from the analysis through the performance response review. However, as a result of this analysis, the team developed a consistent understanding of the infrastructure component definitions and how these particular components may respond to a variety of climatic events. This provided a very solid foundation for the subsequent steps of the risk assessment process.

The final performance response results for this risk assessment are presented in **Figure 4.8**.

Figure 4.8: Performance Response Results

Infrastructure Components	Infrastructure Design	Functionality	Drainage	Maintenance	Emergency Response	Policy / Guidelines / Engineering	Highway Safety	Environmental Effect
Above Ground								
Asphalt - Hot in Place	LT	✓		✓		✓	✓	
Asphalt - Seal Coat	LT	✓		✓		✓	✓	
Pavement Marking		✓		✓		✓	✓	
Shoulders (Including Gravel)	✓	✓	✓	✓	✓	✓	✓	
Barriers		✓		✓		✓	✓	
Curb - Concrete		✓		✓		✓	✓	
Curb - Asphalt		✓		✓		✓	✓	
Luminaires		✓			✓	✓	✓	
Poles	✓	✓		✓		✓		
Signs - Sheeting		✓		✓		✓	✓	
Signs - Wood or metal bases	✓	✓		✓		✓	✓	
Signage - Side Mounted - Over 3.2 m^2	✓	✓		✓		✓	✓	
Signage - Overhead Guide Signs	✓	✓		✓		✓	✓	
Overhead Changeable Message Signs - Weigh Scale	✓	✓		✓		✓	✓	
Ditches	✓	✓	✓	✓	✓	✓	✓	✓
Embankments/Cuts	✓	✓	✓	✓	✓	✓		✓
Natural Hillsides	✓	✓	✓		✓	✓		
Engineered Stabilization Works								
Structures that Cross Streams - Bridges	✓	✓	✓	✓	✓	✓		✓
Structures that Cross Roads - Bridges	✓	✓	✓	✓	✓	✓		
Railways (Drainage Interaction)	✓	✓	✓	✓	✓	✓		
River Training Works - Rip Rap	✓	✓	✓	✓	✓	✓	✓	✓
Retaining Walls - MSE Walls								
Asphalt Spillway and Associated Piping - Above Ground Elements	✓	✓	✓	✓		✓	✓	✓
Below Ground								
Pavement Structure	✓	✓	✓			✓	✓	
Catch Basins	✓	✓	✓	✓		✓	✓	✓
Roadway Drainage Appliances	✓	✓	✓	✓		✓	✓	
Sub-Drains	✓	✓	✓			✓	✓	
Below Ground Third Party Utilities	✓	✓			✓	✓		
Above Ground Third Party Utilities	✓	✓			✓	✓		
Culverts < 3m	✓	✓	✓	✓	✓	✓	✓	✓
Culverts ≥ 3m	✓	✓	✓	✓	✓	✓	✓	✓
Piping/Culvert - Below Ground Elements.	✓	✓	✓	✓	✓	✓	✓	✓
Miscellaneous								
Winter Maintenance		✓	✓	✓		✓	✓	✓
Habitat Features								
Routine Maintenance		✓	✓	✓		✓	✓	
Pavement Marking Repair		✓	✓	✓		✓	✓	
Pavement / Curb/ Barrier / Sign Repair		✓	✓	✓		✓	✓	

4.5 Yes / No Analysis

The next step of the process is to assess the potential for adverse interactions between each climate parameter and each infrastructure component. At this stage of the process, the team is not assessing the magnitude of the risk. Rather, this is a second stage of screening. If the team determines that there can be an adverse interaction between a climatic parameter and an infrastructure component, the interaction is retained within the process for further risk analysis. If the team determines that there may be no material adverse impact, the interaction is eliminated from further risk assessment analysis.

The team completed the yes / no analysis at a teleconferences on December 8 and January 5 and then finalized the analysis at the Workshop on January 18-19, 2011.

The team had identified 38 infrastructure components and 26 climate parameters. Of the 26 climate parameters, two could not be defined to a level acceptable for the risk assessment. Consequently, the team initially considered risk assessment of 912 (38x24) climate / infrastructure interactions. Based on the yes / no analysis, the team identified 178 climate / infrastructure interactions for further risk assessment. Thus, 734 interactions were eliminated from further analysis.

To put this into context, based on the preliminary screening, 734 climate / infrastructure interactions were identified by the team to have no material climate change related risk. The remaining 178 interactions, were identified to have potential risk which was further resolved in subsequent steps of the process.

The results of the yes / no analysis are presented in **Figure 4.9**.

Figure 4.9: Yes / No Analysis

Infrastructure Components	High Temperature	Low Temperature	Average Temperature	Temperature Variability	Freeze/Thaw	Frost / Frost Penetration	Total Annual Rainfall	Extreme High Rainfall	Sustained Rainfall	Longer Sustained Rainfall	Low Rainfall	Prolonged Dry Periods (Drought)	Snow (Frequency)	Snow Accumulation	Snow Storm/ Blizzard	Rain / Snow /Wind	Rain on Snow	Hail / Sleet	Rain on Frozen Ground	Freezing Rain	Visibility	High Wind/ Downburst	Rapid Snow Melt	Snowmelt Driven Peak Flow Events (Spring Freshet)	Ice / Ice Jams	Ground Freezing
Above Ground																										
Asphalt - Hot in Place	Y	Y			Y																					Y
Asphalt - Seal Coat	Y	Y			Y																					Y
Pavement Marking	Y	Y			Y																					
Shoulders (Including Gravel)	Y				Y			Y	Y																	
Barriers								Y																		
Curb - Concrete					Y			Y																		
Curb - Asphalt	Y	Y			Y			Y																		
Luminaires																			Y			Y				
Poles						Y													Y			Y				
Signs - Sheeting																						Y				
Signs - Wood or metal bases																			Y			Y				
Signage - Side Mounted - Over 3.2 m²																			Y			Y				
Signage - Overhead Guide Signs																			Y			Y				
Overhead Changeable Message Signs - Weigh Scale						Y													Y			Y				
Ditches					Y		Y	Y	Y								Y						Y			
Embankments/Cuts	Y				Y		Y	Y	Y								Y						Y			
Natural Hillsides	Y				Y		Y	Y	Y								Y						Y			
Engineered Stabilization Works																										
Structures that Cross Streams - Bridges	Y	Y			Y	Y	Y	Y	Y								Y		Y			Y	Y	Y	Y	
Structures that Cross Roads - Bridges	Y	Y			Y	Y		Y	Y								Y		Y			Y				
Railways (Drainage Interaction)							Y	Y	Y								Y		Y				Y	Y		
River Training Works - Rip Rap							Y	Y	Y														Y	Y	Y	
Retaining Walls - MSE Walls																										
Asphalt Spillway and Associated Piping - Above Ground Elements	Y				Y		Y	Y	Y								Y		Y				Y			
Below Ground																										
Pavement Structure					Y	Y	Y		Y																	Y
Catch Basins					Y		Y	Y	Y								Y	Y	Y				Y			
Roadway Drainage Appliances					Y		Y	Y	Y								Y	Y	Y				Y			
Sub-Drains		Y			Y		Y	Y	Y								Y									
Below Ground Third Party Utilities								Y											Y							
Above Ground Third Party Utilities																			Y							
Culverts < 3m		Y			Y		Y	Y	Y								Y	Y					Y	Y	Y	
Culverts ≥ 3m		Y			Y		Y	Y	Y								Y						Y	Y	Y	
Piping/Culvert - Below Ground Elements.					Y		Y	Y	Y								Y						Y			
Miscellaneous																										
Winter Maintenance		Y			Y	Y		Y					Y		Y		Y		Y			Y	Y		Y	
Habitat Features																										
Routine Maintenance	Y	Y			Y			Y	Y										Y			Y	Y			
Pavement Marking Repair													Y		Y											
Pavement / Curb/ Barrier / Sign Repair													Y		Y											

4.6 Calculated Risk for Each Relevant Interaction

The team calculated the risk for each interaction in two steps. First, PCIC and representatives from the team with climate expertise consulted and assigned probabilities for the climate parameters. Second, at the workshop, the team assigned severity scores for each interaction that passed the yes / no analysis.

During the course of this assessment eleven parameters were removed from evaluation either based on the yes/no analysis or other considerations. These parameters included:

- Average Temperature;
- Temperature Variability;
- Frost /Frost Penetration;
- Longer Sustained Rainfall;
- Low Rainfall;
- Prolonged Dry Periods (Drought);
- Snow Accumulation;
- Snow Storm / Blizzard;
- Rain / Snow / Wind;
- Freezing Rain; and
- Visibility.

These parameters have been excluded from the summary of the risk analysis presented in the following sections.

4.6.1 Probability Scores

There are a number of possible ways to assess the climate change risk using this process. For example, in some studies the practitioner may calculate risk profiles for both the baseline climate and project future climate. Conversely, the team can assign a probability to the climate parameter changing. In this case, the team calculates only one risk profile, that for the changing future climate. In this assessment, the team applied the second approach, calculating the risk profile for a future climate based on the projections and analysis provided by PCIC and sensitivity analysis, as described in **Section 3**.

The team used a probability scoring process and documented their deliberations in a workbook that is summarized in **Figure 4.10**.

The team reviewed available climate data and sensitivity considerations and then expressed a professional opinion based on the consensus of the team. They also assessed the nature of the change in climate, whether the anticipated change was better or worse for the infrastructure, the likely magnitude of that change and their overall confidence in the assessment based on the data availability and approaches used.

Based on the analysis outlined in **Figure 4.10**, the team input probability scores to Protocol Worksheet 3. The probability scores for the interactions considered in the risk assessment are presented in **Figure 4.11**.

Figure 4.10: Probability Scoring Analysis

#	Climate Parameter	Infrastructure Indicator	Will the Interaction Change in the Future?	More-Same-Less?	Projected Change in Magnitude?	Projected Change in Frequency	Robustness of Forecast?	Professional Judgment	Likelihood Score
			Y/N	+ 0 -	H M L	H M L	H M L	Comments	0-7
								P = $\mathcal{F}$(A,B,C,D, & E)	
			A	B	C	D	E	☞	P
1	High Temperature	Day(s) with maximum temperature exceeding 35°C	Y	+	N/A	H	H		6
2	Low Temperature	Day(s) with minimum temperature below -35° C	Y	-	N/A	H	H		6
3	Average Temperature	Average Maximum Temperature Over 7 Days	Y		N/A	H	H	PCIC provides a high confidence projection that temperatures will be increasing. ∴ can infer that average temperature will also increase over time. Since this is an inference, confidence cannot be as high. PCIC states that average temperature has generally higher confidence than min and max Eliminated at Workshop. Not relevant to this infrastructure.	6
4	Temperature Variability	Daily temperature variation of more than 25 °C	Y	-	N/A	H	H	Not strong agreement between climate models. Reduces overall confidence in estimate. Eliminated at Workshop. Not relevant to this infrastructure.	6

Figure 4.10: Probability Scoring Analysis

#	Climate Parameter	Infrastructure Indicator	A: Will the Interaction Change in the Future? (Y/N)	B: More-Same-Less? (+ 0 -)	C: Projected Change in Magnitude? (H M L)	D: Projected Change in Frequency (H M L)	E: Robustness of Forecast? (H M L)	Professional Judgment: Comments ($P = \mathcal{F}(A,B,C,D, \& E)$)	P: Likelihood Score (0-7)
5	Freeze / Thaw	85 or more days where maximum temperature > 0° C and minimum temperature < 0° C Not consecutive days. Concern is total number of events.	Y	-	N/A	L	M	PCIC modeling suggests that this will decrease. At Workshop, Team was concerned because this is an ongoing concern, based on local knowledge. Information at Workshop suggests that a Freeze/Thaw value of -5° C would be more appropriate, given the application of road salt.	5
6	Frost / Frost Penetration	47 or more consecutive days where minimum temperature < 0° C	Y	-	N/A	H	H		6
7	Total Annual Rainfall	406.7 mm	Y	+	N/A	M	M	Good agreement between models.	5
8	Extreme High Rainfall	> 35 mm rain	Y	+	N/A	M	M	Expanded downscaling (EDS) suggests significant increase in extreme rainfall events, especially in the 2100 time frame.	5
9	Sustained Rainfall	≥ 5 consecutive days with > 25 mm rain	Y	+	N/A	H	M	RCMs and EDS suggest significant increase in sustained rainfall events, especially in the 2100 time frame.	5
10	Longer Sustained Rainfall	≥ 23 consecutive days with > 10 mm rain	Y	+	N/A	H	L	Much more rare event. Models show some increase in these events but signal is relatively weak. Eliminated at Workshop. Not relevant to this infrastructure.	4
11	Low Rainfall	≥ 10 consecutive days with precipitation < 0.2 mm	Y	-	N/A	L	M	Eliminated at Workshop. Not relevant to this infrastructure.	5

Figure 4.10: Probability Scoring Analysis

#	Climate Parameter	Infrastructure Indicator	Will the Interaction Change in the Future?	More-Same-Less?	Projected Change in Magnitude?	Projected Change in Frequency	Robustness of Forecast?	Professional Judgment	Likelihood Score
			Y/N	+ 0 -	H M L	H M L	H M L	Comments	0-7
								P = $\mathcal{F}$(A,B,C,D, & E)	
			A	B	C	D	E	☞	P
12	Prolonged Dry Periods (Drought)	≥ 112 consecutive days with precipitation < 0.2 mm	Y	-	N/A	L	M	Models suggest a very slight change in this event. Generally, will be somewhat drier. Not a strong signal from the models indicating not much change. Eliminated at Workshop. Not relevant to this infrastructure.	1
13	Snow (Frequency)	Days with snow fall > 10 cm	Y	-	N/A	L	L	Very little model information. CGCM3 suggests a slight increase, but signal is weak.	2
14	Snow Accumulation	5 or more consecutive days with a snow depth > 60 cm	N	0	N/A	L	L	Very little model information. CGCM3 suggests a no change, but signal is weak. EDS suggests no change at Fraser Lake but suggests a slight decrease at Vanderhoof. PCIC states that there is a clear negative signal in CGCM3, and EDS snow is unreliable. Eliminated at Workshop. Not relevant to this infrastructure.	1
15	Snow Storm / Blizzard	8 or more days with blowing snow	Y	-	N/A	L	L	Models all suggest that there will be a decrease in blizzard events.	2
16	Rain / Snow / Wind	Rain on snow including temperature and wind speed						No model information available. However, blizzard events projected to decrease. Rain / Snow / Wind events are similar in nature. This would suggest a slight decrease in these events. Eliminated at Workshop. Moved to "Rain on Snow".	2
17	Rain on Snow	10 or more consecutive days with rain on snow	Y	-	N/A	L	L	Some disagreement between CGCM3 and EDS information. However, most model information suggests a slight decrease in rain on snow events.	4

Figure 4.10: Probability Scoring Analysis

#	Climate Parameter	Infrastructure Indicator	Will the Interaction Change in the Future?	More-Same-Less?	Projected Change in Magnitude?	Projected Change in Frequency	Robustness of Forecast?	Professional Judgment	Likelihood Score
			Y/N	+ 0 -	H M L	H M **L**	H M **L**	Comments	0-7
								P = $\mathcal{F}$(A,B,C,D, & E)	
			A	B	C	D	E		P
18	Hail / Sleet	Days with precipitation falling as ice particles						No information from models. ⇒ sensitivity analysis on this parameter. Infer similar weather conditions to rain on snow. Suggest using three probability scores: 2, 3 and 4.	*2 3 4*
19	Rain on Frozen Ground	Precipitation > 6 mm/3h No snowfall						Very little model information. What is available seems contradictory. ⇒ sensitivity analysis on this parameter. Infer similar weather conditions to rain on snow. Suggest using three probability scores: 2, 3 and 4.	*2 3 4*
20	Freezing Rain	9 or more days with rain that falls as liquid and freezes on contact						No information from models. ⇒ sensitivity analysis on this parameter. Infer similar weather conditions to rain on snow. Suggest using three probability scores: 2, 3 and 4. Eliminated at Workshop.	*2 3 4*
21	Visibility	≥ 15 hours per year with visibility < 1,000 m						No information from models. ⇒ sensitivity analysis on this parameter. Infer similar weather conditions to rain on snow. Suggest using three probability scores: 2, 3 and 4. Eliminated at Workshop.	*2 3 4*
22	High Wind / Downburst	≥ 8 days with Max winds ≥ 63 km/hr	**Y**	-	**N/A**	**H**	**L**	Model information suggests less frequent periods of high wind for the 2050 period. No information for 2010. No information for Scenario A1B.	*2*

Figure 4.10: Probability Scoring Analysis

#	Climate Parameter	Infrastructure Indicator	Will the Interaction Change in the Future?	More-Same-Less?	Projected Change in Magnitude?	Projected Change in Frequency	Robustness of Forecast?	Professional Judgment	Likelihood Score
			Y/N	+ 0 -	H M L	H M L	H M L	Comments	0-7
								P = $\mathcal{F}$(A,B,C,D, & E)	
			A	B	C	D	E	☞	P
23	Rapid Snow Melt	Snow melt > 9 mm/3h	**Y**	-	**N/A**	**M**	**L**	Only information from CGCM3.	*4*
24	Snow Driven Peak Flow Events	N/A						Consensus of Team at Workshop established this as a likely event. Based on local knowledge of the infrastructure.	*5*
25	Ice / Ice Jams	N/A						No direct information from models. Warmer climate overall. Less frost / frost penetration. Higher annual rainfall. ⇒ sensitivity analysis on this parameter. Suggest using three probability scores: 2, 3 and 4	*2* *3* *4*
26	Ground Freezing	Number of days below -5 °C	**Y**	-	**N/A**	**H**	**M**	Models and EDS agree that there will be significantly fewer events of this type.	*6*

Figure 4.11: Probability Scores

Infrastructure Components	High	Low	Freeze/Thaw	Frost / Frost Penetration	Total Annual Rainfall	Extreme High Rainfall	Sustained Rainfall	Snow (Frequency)	Snow Storm/ Blizzard	Rain on Snow	Hail / Sleet	Rain on Frozen Ground	High Wind/ Downburst	Rapid Snow Melt	Snowmelt Driven Peak Flow Events (Spring Freshet)	Ice / Ice Jams	Ground Freezing
Above Ground																	
Asphalt - Hot in Place	6	6	5														6
Asphalt - Seal Coat	6	6	5														6
Pavement Marking	6	6	5														
Shoulders (Including Gravel)	6		5			5	5										
Barriers						5											
Curb - Concrete			5			5											
Curb - Asphalt	6	6	5			5											
Luminaires												3	2				
Poles				6								3	2				
Signs - Sheeting													2				
Signs - Wood or metal bases												3	2				
Signage - Side Mounted - Over 3.2 m^2												3	2				
Signage - Overhead Guide Signs												3	2				
Overhead Changeable Message Signs - Weigh Scale				6								3	2				
Ditches			5		5	5	5			4				4			
Embankments/Cuts	6		5		5	5	5			4				4			
Natural Hillsides	6		5		5	5	5			4				4			
Engineered Stabilization Works																	
Structures that Cross Streams - Bridges	6	6	5	6	5	5	5			4		3	3	4	5	3	
Structures that Cross Roads - Bridges	6	6	5	6		5	5			4		3	3				
Railways (Drainage Interaction)					5	5	5			4		3		4	5		
River Training Works - Rip Rap					5	5	5							4	5	3	
Retaining Walls - MSE Walls																	
Asphalt Spillway and Associated Piping - Above Ground Elements	6		5		5	5	5			4		3		4			
Below Ground																	
Pavement Structure			5	6	5		5										6
Catch Basins			5		5	5	5			4	3	3		4			
Roadway Drainage Appliances			5		5	5	5			4	3	3		4			
Sub-Drains		6	5		5	5	5			4							
Below Ground Third Party Utilities						5						3					
Above Ground Third Party Utilities												3					
Culverts < 3m		6	5		5	5	5			4	3			4	5	3	
Culverts ≥ 3m		6	5		5	5	5			4				4	5	3	
Piping/Culvert - Below Ground Elements.			5		5	5	5			4				4			
Miscellaneous																	
Winter Maintenance		6	5	6		5		2	2	4		3	2	4		3	
Habitat Features																	
Routine Maintenance	6	6	5			5	5					3	2	4			
Pavement Marking Repair								2	2								
Pavement / Curb/ Barrier / Sign Repair								2	2								

4.6.2 Severity Scores

The team assigned the severity score for each relevant climate-infrastructure interaction at the workshop in January. The implications and potential consequences for each interaction were discussed in turn by the team.

In some ways, the assignment of severity scores was much more straightforward than the assignment of probability scores. The team has direct, hands-on, experience in managing similar events over the life of the highway. This experience provides a solid foundation for the opinions expressed by the team membership.

During the workshop, there were occasions where team members would disagree about potential outcomes of a particular interaction. However, the team was able to fully examine these situations and arrive at a consensus regarding the severity scoring.

It is notable that the team assigned a number of severity scores of "0". This is permitted by the Protocol. This allows a further level of screening and review. These items initially passed the yes/no analysis but, upon more detailed review, were determined to have immaterial adverse outcomes from the climate-infrastructure interaction. This ensures that the assignment of a low risk score was based on a considered evaluation of the situation.

The severity scores assigned by the team are presented in **Figure 4.12**.

Figure 4.12: Severity Scores

Infrastructure Components	High Temperature	Low Temperature	Freeze/Thaw	Frost / Frost Penetration	Total Annual Rainfall	Extreme High Rainfall	Sustained Rainfall	Snow (Frequency)	Snow Storm/ Blizzard	Rain on Snow	Hail / Sleet	Rain on Frozen Ground	High Wind/ Downburst	Rapid Snow Melt	Snowmelt Driven Peak Flow Events (Spring Freshette)	Ice / Ice Jams	Ground Freezing
Above Ground																	
Asphalt - Hot in Place	3	0	1														2
Asphalt - Seal Coat	1	0	1														2
Pavement Marking	0	0	1														
Shoulders (Including Gravel)	0		1			4	3										
Barriers						2											
Curb - Concrete			2			2											
Curb - Asphalt	0	0	1			2											
Luminaires												0	0				
Poles				0								0	1				
Signs - Sheeting													0				
Signs - Wood or metal bases												0	0				
Signage - Side Mounted - Over 3.2 m^2												0	2				
Signage - Overhead Guide Signs												0	2				
Overhead Changeable Message Signs - Weigh Scale				0								0	2				
Ditches			0		2	4	1			2				3			
Embankments/Cuts	0		1		2	4	3			2				4			
Natural Hillsides	0		1		2	2	2			2				3			
Engineered Stabilization Works																	
Structures that Cross Streams - Bridges	4	1	3	0	2	3	2			2		1	0	1	3	2	
Structures that Cross Roads - Bridges	4	1	3	0		3	2			2		1	0				
Railways (Drainage Interaction)					2	2	2			2		0		2	2		
River Training Works - Rip Rap					2	3	2							1	3	2	
Retaining Walls - MSE Walls																	
Asphalt Spillway and Associated Piping - Above Ground Elements	0		2		2	5	2			3		1		2			
Below Ground																	
Pavement Structure			1	0	2		2										1
Catch Basins			2		1	5	2			3	0	2		2			
Roadway Drainage Appliances			2		1	5	2			3	0	2		2			
Sub-Drains		0	1		1	2	2			1							
Below Ground Third Party Utilities						2						0					
Above Ground Third Party Utilities												2					
Culverts < 3m		0	1		1	5	3			3	1			4	5	3	
Culverts ≥ 3m		0	1		1	3	2			1				1	4	3	
Piping/Culvert - Below Ground Elements.			1		1	4	2			3				2			
Miscellaneous																	
Winter Maintenance		1	4	0		4		1	0	4		5	2	1		3	
Habitat Features																	
Routine Maintenance	1	1	3			5	2					1	2	1			
Pavement Marking Repair								0	0								
Pavement / Curb/ Barrier / Sign Repair								1	0								

4.6.3 Risk Outcomes

Based on the probability and severity scores, the team calculated the risk outcomes using the equation described in **Section 4.2**:

$R = P \times S$

Where:

R = Risk
P = Probability of the interaction
S = Severity of the interaction

Each outcome was assigned a high, medium or low risk score based on the risk tolerances defined in **Section 4.1.2** and color-coded, as indicated in **Figure 4.13.**

Figure 4.13: Risk Tolerance Threshold Color Codes

Risk Range	Threshold	Response
< 12	Low Risk	• No immediate action necessary
12 – 36	Medium Risk	• Action may be required • Engineering analysis may be required
> 36	High Risk	• Immediate action required

The calculated risk scores arising from this assessment are presented in **Figure 4.14**.

Figure 4.14: Summary of Climate Change Risk Assessment Scores

Infrastructure Components	High Temperature	Low Temperature	Freeze/Thaw	Total Annual Rainfall	Extreme High Rainfall	Sustained Rainfall	Snow (Frequency)	Rain on Snow	Hail / Sleet	Rain on Frozen Ground	High Wind/ Downburst	Rapid Snow Melt	Snowmelt Driven Peak Flow Events (Spring Freshet)	Ice / Ice Jams	Ground Freezing
Above Ground															
Asphalt - Hot in Place	18	0	5												12
Asphalt - Seal Coat	6	0	5												12
Pavement Marking	0	0	5												
Shoulders (Including Gravel)	0		5		20	15									
Barriers					10										
Curb - Concrete			10		10										
Curb - Asphalt	0	0	5		10										
Luminaires										0	0				
Poles										0	2				
Signs - Sheeting											0				
Signs - Wood or metal bases										0	0				
Signage - Side Mounted - Over $3.2\ m^2$										0	4				
Signage - Overhead Guide Signs										0	4				
Overhead Changeable Message Signs - Weigh Scale										0	4				
Ditches			0	10	20	5		8				12			
Embankments/Cuts	0		5	10	20	15		8				16			
Natural Hillsides	0		5	10	10	10		8				12			
Engineered Stabilization Works															
Structures that Cross Streams - Bridges	24	6	15	10	15	10		8		3	0	4	15	6	
Structures that Cross Roads - Bridges	24	6	15		15	10		8		3	0				
Railways (Drainage Interaction)				10	10	10		8		0		8	10		
River Training Works - Rip Rap				10	15	10						4	15	6	
Retaining Walls - MSE Walls															
Asphalt Spillway and Associated Piping - Above Ground Elements	0		10	10	25	10		12		3		8			
Below Ground															
Pavement Structure			5	10		10									6
Catch Basins			10	5	25	10		12	0	6		8			
Roadway Drainage Appliances			10	5	25	10		12	0	6		8			
Sub-Drains		0	5	5	10	10		4							
Below Ground Third Party Utilities					10					0					
Above Ground Third Party Utilities										6					
Culverts < 3m		0	5	5	25	15		12	3			16	25	9	
Culverts ≥ 3m		0	5	5	15	10		4				4	20	9	
Piping/Culvert - Below Ground Elements.			5	5	20	10		12				8			
Miscellaneous															
Winter Maintenance		6	20		20		2	16		15	4	4		9	
Habitat Features															
Routine Maintenance	6	6	15		25	10				3	4	8			
Pavement Marking Repair							0								
Pavement / Curb/ Barrier / Sign Repair							2								

4.6.4 Sensitivity Analysis Results

As described in **Section 3.4.1**, we conducted sensitivity analysis for three Climate Parameters. These were:

- Climate Parameter 19, Rain on Frozen Ground
- Climate Parameter 25, Ice / Ice Jams
- Climate Parameter 26, Ground Freezing

For parameters 19 and 25, the probability scoring was adjusted to test the risk volatility arising from slightly increasing the likelihood of the parameter changing over the time horizon of the assessment.

For Parameter 26, the team determined that the predicted change in ground freezing would be beneficial with respect to asphalt surfaces and assigned a severity score of "2", indicating little, or no, impact on the infrastructure from this event. The team had some debate about this score varying between "1" and "2" prior to generally agreeing on the assigned score. PCIC and the team assigned a probability score of "6" to this event. The combination of these two scores resulted in a risk score of "12", just marginally medium risk. To test this outcome, we adjusted the severity score to a value of "1". The impact of this sensitivity adjustment was to reduce the overall risk profile for this interaction to very low risk. Given the high probability score, these interactions are extremely sensitive to severity score results, especially for low severity events. Based on the sensitivity analysis, we have concluded that these interactions are unlikely to present significant risk to the highway infrastructure.

The adjusted probability scores are presented in **Figure 4.15**.

Figure 4.15: Probability and Severity Score Adjustments for Sensitivity Analysis

#	Parameter	Scores			
		Probability		Severity	
		Workshop	Sensitivity	Workshop	Sensitivity
19	Rain on Frozen Ground	3	4		
25	Ice / Ice Jams	3	4		
26	Ground Freezing			2	1

The results of the sensitivity analysis are presented in **Figure 4.16**.

The workbook used to complete the sensitivity analysis is presented in **Appendix G**.

In this chart, the risk outcomes that changed as a result of the sensitivity analysis are color-coded as follows:

Increased Risk Outcomes:

Decreased Risk Outcomes:

Figure 4.16: Climate Change Risk Assessment Sensitivity Analysis

Infrastructure Components	High Temperature	Low Temperature	Freeze/Thaw	Total Annual Rainfall	Extreme High Rainfall	Sustained Rainfall	Snow (Frequency)	Rain on Snow	Hail / Sleet	Rain on Frozen Ground	High Wind/ Downburst	Rapid Snow Melt	Snowmelt Driven Peak Flow Events (Spring Freshet)	Ice / Ice Jams	Ground Freezing
Above Ground	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Asphalt - Hot in Place	18	0	5												6
Asphalt - Seal Coat	6	0	5												6
Pavement Marking	0	0	5												
Shoulders (Including Gravel)	0		5		20	15									
Barriers					10										
Curb - Concrete			10		10										
Curb - Asphalt	0	0	5		10										
Luminaires										0	0				
Poles										0	2				
Signs - Sheeting											0				
Signs - Wood or metal bases										0	0				
Signage - Side Mounted - Over 3.2 m²										0	4				
Signage - Overhead Guide Signs										0	4				
Overhead Changeable Message Signs - Weigh Scale										0	4				
Ditches			0	10	20	5		8				12			
Embankments/Cuts	0		5	10	20	15		8				16			
Natural Hillsides	0		5	10	10	10		8				12			
Engineered Stabilization Works															
Structures that Cross Streams - Bridges	24	6	15	10	15	10		6		4	0	4	15	8	
Structures that Cross Roads - Bridges	24	6	15		15	10		6		4	0				
Railways (Drainage Interaction)				10	10	10		6		0		8	10		
River Training Works - Rip Rap				10	15	10						4	15	8	
Retaining Walls - MSE Walls															
Asphalt Spillway and Associated Piping - Above Ground Elements	0		10	10	25	10		12		4		8			
Below Ground															
Pavement Structure			5	10		10									6
Catch Basins			10	5	25	10		12	0	8		8			
Roadway Drainage Appliances			10	5	25	10		12	0	8		8			
Sub-Drains		0	5	5	10	10		4		8					
Below Ground Third Party Utilities					10					0					
Above Ground Third Party Utilities										8					
Culverts < 3m		0	5	5	25	15		12	3			16	25	12	
Culverts ≥ 3m		0	5	5	15	10		4				4	20	12	
Piping/Culvert - Below Ground Elements.			5	5	20	10		12				8			
Miscellaneous															
Winter Maintenance		6	20		20		2	16		20	4	4		12	
Habitat Features															
Routine Maintenance	6	6	15		25	10				4	4	8			
Pavement Marking Repair							0								
Pavement / Curb/ Barrier / Sign Repair							2								

4.7 Combined Events

The team contemplated several combined events and cumulative impacts in their assessment.

These included:

- **Climate Parameter 5: Freeze / Thaw**
  - The number of days with minimum temperatures less than 0 ^{o}C and maximum temperatures greater than 0 ^{o}C
  - At the workshop this parameter was adjusted to the number of days with minimum temperatures less than -5 ^{o}C and maximum temperatures greater than -5 ^{o}C
    - This was based on the application of road salt depressing the freezing point on the highway

- **Climate Parameter 15: Snow Storm / Blizzard**
  - The combined impact of snow and wind

- **Climate Parameter 16: Rain / Snow / Wind**
  - Rain on snow including higher temperatures and wind considerations
    - At the workshop the team removed this parameter from the assessment.
    - The team agreed that the primary issue in this regard was rain on snow, which was covered by Climate Parameter 17.

- **Climate Parameter 17: Rain on Snow**
  - This parameter represents the combined impact of rain events during winter conditions.

- **Climate Parameter 19: Rain on Frozen Ground**
  - Represents the impact of rain falling on frozen surfaces
    - These events could lead to ice accretion and traffic safety concerns.

- **Climate Parameter 20: Freezing Rain**
  - Days with greater than 6 mm in 3 hours of precipitation when the temperature is less than 0 ^{o}C
    - At the workshop the team eliminated this parameter from the analysis in favour of Climate Parameter 19, which they believed provided a better definition of the potential risk factors.

- **Climate Parameter 24: Snowmelt Driven Peak Flow Events (Spring Freshet)**
  - Days with greater than 6 mm in 3 hours of precipitation when the temperature is less than 0 ^{o}C

- At the workshop the team eliminated this parameter from the analysis in favour of Climate Parameter 19, which they believed provided a better definition of the potential risk factors.

4.8 Risks Ranking

The team ranked risks into three categories:

1. Low or No Material Risk
2. Medium Risk
3. High Risk

The team originally conducted the risk assessment on 178 potential climate-infrastructure interactions. Based on the analysis the team identified:

- 137 interactions with low or no material risk;
- 41 interactions with medium risk; and
- No interactions with high risk.

4.9 Items Forwarded to Step 4 – Engineering Analysis

Subsequent to the workshop, the team identified four climate-infrastructure interactions that required further resolution through Step 4 – Engineering Analysis. These included:

- Catch Basins & 24-hour Duration Extreme Rainfall
- Culverts < 3 m & 24-hour Duration Extreme Rainfall
- Concrete Bridges & Extreme High Temperature
- Concrete Bridges & Extreme Low Temperature

The engineering analysis of these three interactions is detailed in **Section 5**.

4.10 Data Sufficiency

The team was satisfied with the quality, quantity and integrity of the data used for the risk assessment. As previously discussed, the team was not able to resolve data concerns for Visibility.

The team excluded this parameter from the risk assessment process and recommended it for further study.

The team addressed other potential data gaps through sensitivity analyses.

In general, the experience of the team compensated for any gaps in technical or design data.

4.11 *Discussion*

4.11.1 General

The team originally conducted the risk assessment on 178 potential climate-infrastructure interactions. Based on the analysis the team identified that:

- 137, or 77% of the interactions had low or no material risk;
- 41, or 23% of the interactions had medium risk; and
- There were no interactions with high risk.

Of the 41 medium level risks, most were relatively minor with 26 interactions generating risk scores in the range 12 to 18. Only 15 interactions generated risk scores in excess of 18 and there were no risk scores in excess of 25.

The analysis did not expose any high-risk interactions. That is, for the most part this stretch of highway infrastructure is relatively robust. The team evaluated this outcome at the workshop and reached a number of conclusions:

- The highway is very mature and has undergone ongoing refurbishment throughout its life resulting in higher levels of built in resiliency.
- Due to the age of the infrastructure, the engineering, operations and maintenance practices have reached a high level of maturity.
- These practices generally address the significant weather events contemplated by the assessment.
- The risk profile is somewhat attenuated because the infrastructure team has already developed practices that mitigate the risk.

For the most, the risks that were identified were generally associated with potential drainage issues arising from predicted higher levels of precipitation over the time horizon of the assessment.

There were also two medium risk scenarios resulting from higher maximum daily temperatures impacting bridge structures.

The sensitivity analysis did not materially change these results.

5 Step 4 – Engineering Analysis

In this step the team assessed the impact of projected climate change loads for four climate-infrastructure combinations:

1. Catch Basins & 24-hour Duration Extreme Rainfall
2. Culverts < 3 m & 24-hour Duration Extreme Rainfall
3. Concrete Bridges & Extreme High Temperature
4. Concrete Bridges & Extreme Low Temperature

Vulnerability exists when infrastructure has insufficient capacity to withstand the projected or anticipated loads that may be placed on it. Resiliency exists when the infrastructure has sufficient capacity to withstand increasing loads resulting from climate change.

Engineering Analysis requires the assessment of the various factors that affect load and capacity of the infrastructure. Based on this assessment, indicators or factors are determined in order to relatively rank the potential vulnerability of the infrastructure elements to various climate effects.

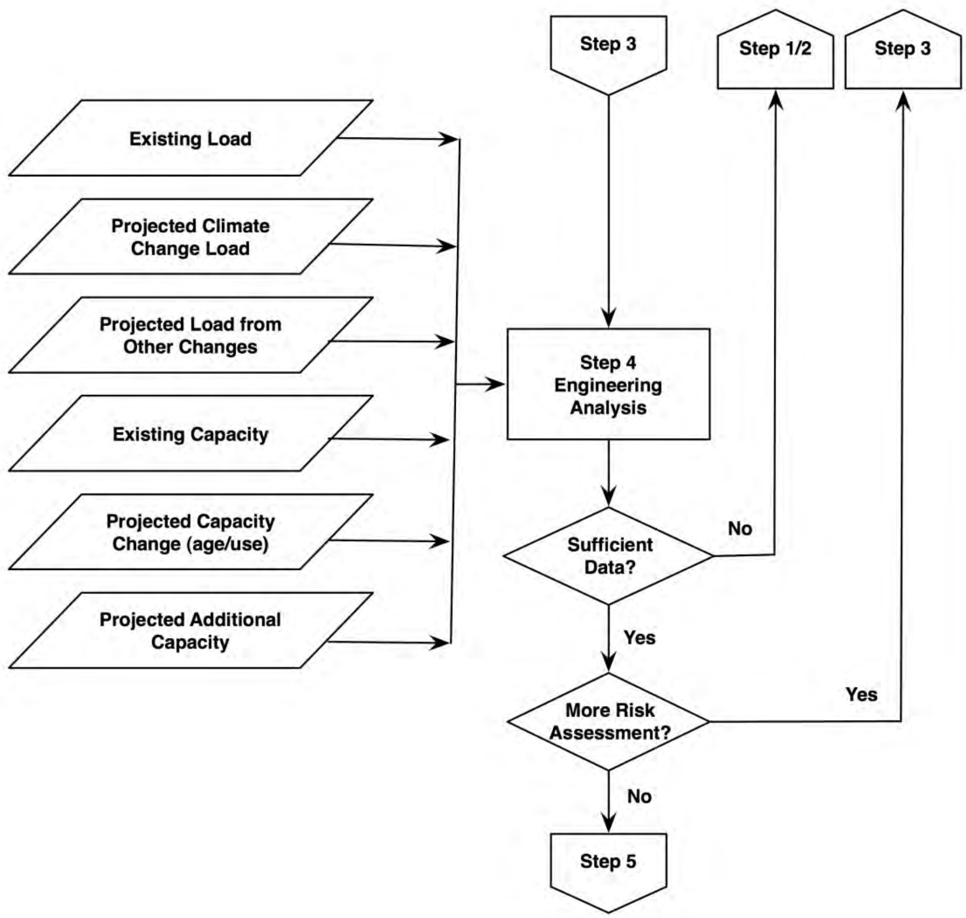
Much of the data required for Engineering Analysis may not exist or may be very difficult to acquire. Engineering Analysis requires the application of multi-disciplinary professional judgment. The results of the analysis yield a set of parameters that can be ranked relative to each other, based on the professional judgment of the team. This can be used to rank the relative vulnerability or resiliency of the infrastructure.

BC MoTI formed a small sub-committee of the team to focus on this activity. The work was completed subsequent to the workshop over the period January 20, 2011 through February 11, 2011.

The process flowchart for Step 4 of the Protocol is presented in **Figure 5.1**.

The completed Worksheet 4 from the Protocol is presented in **Appendix H**.

Figure 5.1: Engineering Analysis Process Flowchart



5.1 *Engineering Analysis of Catch Basins*

Even though the Ministry Standards require catch basins to be designed for 5-minute duration rainfall with 5-year return period, the team analyzed catch basins using 24-hour duration intense rainfall with a 5-year return period in order to provide a consistent scale for comparing vulnerability with other infrastructure components.

The IDF curves for different duration rainfall events are generally parallel to each other. The team assumed the effects of climate change load would be the same for each curve and the vulnerability calculation of load and capacity would yield the same ratio. However, the capacity deficit calculation will show an increase looking at a 5-minute event over a 24-hour event. The 24-hour period is used for comparison with other regional highway forecast climate case studies in BC.

5.2 Engineering Analysis of Culverts

Similar to the engineering analysis of catch basins, the team analyzed the 24-hr duration extreme rainfall events for culverts < 3m, as a high level assessment. This approach provides a consistent scale for comparing vulnerability with other infrastructure components. In addition, the 24-hour duration analysis will allow comparison between the Yellowhead Highway and Coquihalla Highway analyses.

As an extension of this analysis, the team conducted an example engineering analysis of the Ross Creek Culvert, a typical single 1.2m diameter, 18m length corrugated steel pipe, as an illustration of how further hydrotechnical analysis could be applied to develop more information on potential drainage issues. The Ross Creek analysis is presented in **Section 5.7**.

5.3 Calculation of Total Load

The team calculated total load for the interactions identified in Step 3 guided by the Protocol and using the Protocol worksheet to document their deliberations. The results of the total load analysis are presented in **Figure 5.2**.

Figure 5.2: Total Load

Infrastructure Component	Existing Load	Climate Load	Other Change Load	Total Load
	L_E	L_C	L_O	$L_T = L_E+L_C+L_O$
Catch Basins & 24-hour Duration Extreme Rainfall (mm/24hr)				
2050s	29.3	4.5	0.0	33.8
2100s	29.3	12.1	0.0	41.4
Basis for Determination ☞	We assumed these structures were originally designed for a 1:5 year return period. Referencing the 1:5 year return period to 24 hour rainfall data from the Rainfall Frequency Atlas for Canada (HOGG, 1985) yields rainfall as 29.3 mm / 24 hour for the Vanderhoof area. This is the unfactored design load used for comparison.	The future peak rainfall event will likely increase in frequency, but the change in magnitude is unknown. Therefore we assumed the climate load will equal to the average increase of the A1B and A2 models. The average increase in the 24 hour extreme rainfall with return period of 1:5 year are 15.2% (4.5mm / 24 hour) and 41.3% (12.1 mm / 24 hour) for the 2050's and 2100's scenarios, respectively.	Land use changes (logging, pine beetle) could increase amounts of water but we assume little affect on this structure as it is part of the internal road drainage and likely not affected by the watershed.	

Figure 5.2: Total Load

Infrastructure Component	Existing Load	Climate Load	Other Change Load	Total Load
	L_E	L_C	L_O	$L_T = L_E+L_C+L_O$
		The increase for the 2100's scenario may be higher due to higher uncertainty in the model. However we assumed that would be considered in the model results already.		
Culverts < 3 m & 24 –hour Duration Extreme Rainfall (mm/24hr)				
2050s	45	7.0	4.5	56.5
2100s	45	24.3	4.5	73.8
Basis for Determination	We assumed these structures were originally designed for a 1:100 year return period. Referencing the 1:100 year return period to 24 hour rainfall data from the Rainfall Frequency Atlas for Canada (HOGG, 1985) yields rainfall as 45 mm / 24 hour for the Vanderhoof area. This is the unfactored design load used for comparison.	The results from the climate models (A1B and A2) were used to evaluate the climate load. The average increase in the 24 hour extreme rainfall with return period of 1:100 year are 15.5% (7 mm / 24 hour) and 54% (24.3 mm / 24 hour) for the 2050's and 2100's scenarios, respectively. The increase for the 2100's scenario may be higher due to higher uncertainty in the model. However we assumed that would be considered in the model results already.	Parts of the forest in this area were affected by pine beetle infestation. However the forest will likely grow back in the future. Therefore the effects of pine beetle will likely become less significant for the 2050's and 2100's scenarios. The surface vegetation may also change due to logging, forest fires, land development, etc. Such activities could increase the load by increasing surface runoff. We assume a 10% (4.5 mm / 24 hour) increase in load.	
Concrete Bridges & Extreme High Temperature (^{o}C)				
2050s	34.8	0.9		35.7
2100s	34.8	2.7		37.5

Figure 5.2: Total Load

Infrastructure Component	Existing Load	Climate Load	Other Change Load	Total Load
	L_E	L_C	L_O	$L_T = L_E+L_C+L_O$
Basis for Determination ☞	For high temp indicator for structures in area used 34.8°C (though some temp spikes up to 45°C)	The averages of results from the two climate models (A1B and A2) were used to evaluate the climate load. The average increases in high temperature with return period of 1:50 year are 2.56% and 7.69% for the 2050's and 2100's scenarios, respectively. The increase for the 2100's scenario may be higher due to higher uncertainty in the model. However we assumed that would be considered in the model results already.		
Concrete Bridges and Low Temperature (^oC)				
2050s	-47.0	-1.8		-48.8
2100s	-47.0	-6.4		-53.4
Basis for Determination ☞	Lowest temperature found in Vanderhoof in 1984	The averages of results from the two climate models (A1B and A2) were used to evaluate the climate load. The average decrease in low temperature with return period of 1:50 year are -3.72% and -13.59% for the 2050's and 2100's scenarios, respectively. The decrease for the 2100's scenario may be higher due to higher uncertainty in the model. However we assumed that would be considered in the model results already.		

5.4 *Calculation of Total Capacity*

The team calculated total capacity for the interactions identified in Step 3 guided by the Protocol and using the Protocol worksheet to document their deliberations. The results of the capacity analysis are presented in **Figure 5.3**.

Figure 5.3: Total Capacity

Infrastructure Component	Existing Capacity	Climate Capacity	Other Change Capacity	Total Capacity
	C_E	C_M	C_A	$C_T = C_E+C_M+C_A$
Catch Basins & Extreme 24-hour Duration Rainfall (mm/24hr)				
2050s	29.3	0.0	-1.5	27.8
2100s	29.3	0.0	-1.5	27.8
Basis for Determination ☞	We cannot verify if the designers added capacity as a safety factor to this component. Also due to lack of weather data prior to the time of construction in the 1960's, we cannot verify if there have been changes to climate condition. We assumed the existing capacity to be the same as the design load, and there was no change in climate condition since the original construction.	No increase was used for this component.	Maturing or degradation of the culverts could reduce the capacity by 5% (1.5 mm / 24 hour). Maintenance will be required when the culverts are blocked by debris and whenever necessary.	
Culverts < 3 m & Extreme 24-hour Duration Rainfall (mm/24hr)				
2050s	45	0	-2.3	42.8
2100s	45	0	-2.3	42.8

Figure 5.3: Total Capacity

Infrastructure Component	Existing Capacity	Climate Capacity	Other Change Capacity	Total Capacity
	C_E	C_M	C_A	$C_T = C_E + C_M + C_A$
Basis for Determination ☞	We cannot verify if the designers added capacity as a safety factor to this component. Also due to lack of weather data prior to the time of construction in the 1960's, we cannot verify if there have been changes to climate condition. We assumed the existing capacity to be the same as the design load, and there was no change in climate condition since the original construction.	No reduction was used for this component. Maintenance will be required when the culverts are blocked by debris and whenever necessary.	Maturing or degradation of the culverts could reduce the capacity by 5% (2.3 mm / 24 hour).	
Concrete Bridges & Extreme High Temperature **(°C)**				
2050s	34.4			34.4
2100s	34.4			34.4
Basis for Determination ☞	Bridges built late 1960's early 1970's. In 1970's bridges were designed according to: For Steel max temp 120°F = 49°C For Concrete take average temp of 59°F (15°C) and for cold climates go to a rise of 35°F = 94°F (34.4°C). (Standards - Thermal Forces section: the range is "figured from an assumed temperature at the time of erection." We used 59°F as the assumed temp for standard today is 15°C.) Citation: Standard Specifications for Highway Bridges: Adopted by the American Association of State Highway Officials, Tenth Ed.			

Figure 5.3: Total Capacity

Infrastructure Component	Existing Capacity	Climate Capacity	Other Change Capacity	Total Capacity
	C_E	C_M	C_A	$C_T = C_E + C_M + C_A$
	1969, p. 25.			
Concrete Bridges and Low Temperature (°C)				
2050s	-45.0			-45.0
2100s	-45.0			-45.0
Basis for Determination ☞	Bridges built late 1960's early 1970's. Using the current bridge design standards: Using Max and Min average daily temperatures from an iso-temperature map. For Steel structures use max min and decrease by 15°C to get -55°C For Concrete take max min average temp of 40°F and decrease by 5°C to get -45°C Citation: Canadian Highway Bridge Design Code, CSA, Nov 2006			

5.5 *Vulnerability Evaluation*

Based on the results generated for total load and total capacity, the team calculated the vulnerability ratios for the interactions.

The vulnerability ratio is defined as:

$$V_R = \frac{L_T}{C_T}$$

Where:

L_T = Total Load
C_T = Total Capacity

The infrastructure component is deemed to be vulnerable when $V_R > 1$. That is, the projected load is greater than the projected capacity. In this case, the team is projecting a situation where there is a potential failure condition arising from the climate-infrastructure interaction. This does not mean that the infrastructure component will definitely fail. Rather, it suggests that the team is contemplating a set of realistic, foreseeable states, where the infrastructure could conceivably fail. This suggests that there is a rational basis for concluding that the infrastructure is at risk.

The infrastructure component is deemed to be resilient when $V_R < 1$. That is, the projected load is less than the projected capacity. In this case, the team is projecting a situation where there is a potential non-failure condition arising from the climate-infrastructure interaction. This does not mean that the infrastructure component will definitely not fail. Rather, it suggests that the team is contemplating a set of realistic, foreseeable states, where the infrastructure could conceivably continue to operate at an acceptable level of service. This suggests that there is a rational basis for concluding that the infrastructure is not at risk.

The results from the vulnerability evaluation are presented in **Figure 5.4**.

Figure 5.4: Vulnerability

Infrastructure Component	Total Load	Total Capacity	Vulnerability
	L_T	C_T	$V_R = \frac{L_T}{C_T}$
Catch Basins & 24-hour Duration Extreme Rainfall (mm/24hr)			
2050s	33.8	27.8	1.21
2100s	41.4	27.8	1.49
Culverts < 3 m & 24-hour Duration Extreme Rainfall (mm/24hr)			
2050s	56.5	42.8	1.32
2100s	73.8	42.8	1.73
Concrete Bridges & Extreme High Temperature (°C)			
2050s	35.7	34.4	1.04
2100s	37.5	34.4	1.09
Concrete Bridges & Extreme Low Temperature (°C)			

Figure 5.4: Vulnerability

Infrastructure Component	Total Load	Total Capacity	Vulnerability
	L_T	C_T	$V_R = \frac{L_T}{C_T}$
2050s	-48.8	-45.0	1.08
2100s	-53.4	-45.0	1.19

5.6 *Calculation of Capacity Deficit*

Based on the results generated for total load and total capacity, the team calculated the capacity deficits for the three interactions.

The capacity deficit is defined as:

$$C_D = L_T - C_T$$

Where:

L_T = Total Load
C_T = Total Capacity

This calculation is an adjunct to the vulnerability evaluation conducted in **Section 5.3**. It not only indicates whether or not the infrastructure component is vulnerable but it also gives a sense of the magnitude of that vulnerability or resiliency.

The infrastructure component is deemed to be vulnerable when $C_D > 1$. Consistent with the discussion of V_R, the projected load is greater than the projected capacity. In this case, the team is projecting a situation where there is a potential failure condition arising from the climate-infrastructure interaction. This does not mean that the infrastructure component will definitely fail. Rather, it suggests that the team is contemplating a set of realistic, foreseeable states, where the infrastructure could conceivably fail. This suggests that there is a rational basis for concluding that the infrastructure is at risk.

The infrastructure component is deemed to be resilient when $C_D < 1$. Consistent with the discussion of V_R, the projected load is less than the projected capacity. In this case, the team is projecting a situation where there is a potential non-failure condition arising from the climate-infrastructure interaction. This does not mean that the infrastructure component will definitely not fail. Rather, it suggests that the team is contemplating a set of realistic, foreseeable states, where the infrastructure could conceivably continue to operate at an acceptable level of service. This suggests that there is a rational basis for concluding that the infrastructure is not at risk.

The results from the vulnerability evaluation are presented in **Figure 5.5**.

Figure 5.5: Capacity Deficit

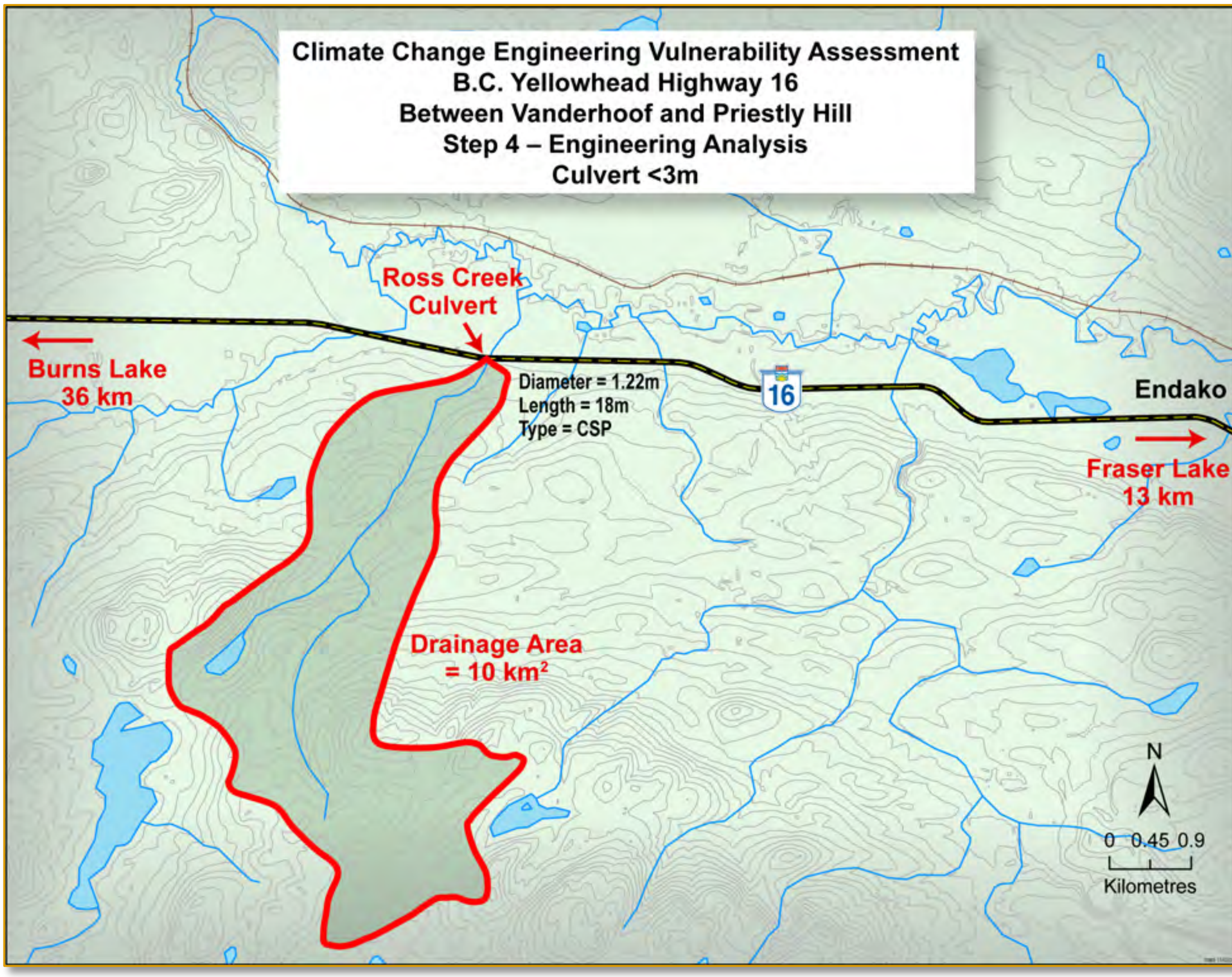
Infrastructure Component	Total Load	Total Capacity	Capacity Deficit
	L_T	C_T	$C_D = L_T - C_T$
Catch Basins & 24-hour Extreme Rainfall (mm/24hr)			
2050s	33.8	27.8	5.92
2100s	41.4	27.8	13.57
Culverts < 3 m & 24-hour Extreme Rainfall (mm/24hr)			
2050s	56.5	42.8	13.73
2100s	73.8	42.8	31.05
Concrete Bridges & Extreme High Temperature (°C)			
2050s	35.7	34.4	1.29
2100s	37.5	34.4	3.08
Concrete Bridges & Extreme Low Temperature (°C)			
2050s	-48.8	-45.0	-3.75
2100s	-53.4	-45.0	-8.39

5.7 *Ross Creek Culvert Analysis – An Example*

To evaluate the vulnerability of culverts < 3m due to future climate change, a detailed assessment was done on the Ross Creek Culvert, a typical single 1.2m diameter, 18m length corrugated steel pipe. We chose this culvert because it would best represent culverts < 3m. It has typical watershed characteristics, similar to the other culverts in the study area. Also we consider this culvert to be problematic due to changes in the watershed, such as pine beetle infestation, and will be vulnerable to future changes.

As outlined in **Figure 5.6**, the Ross Creek culvert is located approximately 13km west of Endako on Highway 16. The drainage area is 10km^2 with an average slope of 6%. However the channel flattens and the slope near the culvert, close to Endako River, is about 0.5% to 2%. The vegetation is mostly forest that is affected by pine beetle infestation.

Figure 5.6: Location and Physical Features of the Ross Creek Culvert



We followed the PIEVC recommended approach on analysing the vulnerability by calculating the existing load from the watershed, future change load based on the results derived from the climate model, the existing culvert capacity, and future change in capacity of the Ross Creek Culvert. Due to limited culvert and channel information, we made several assumptions that should be confirmed in the field to verify the validity of the results.

5.7.1 Culvert Total Load

The current Ministry Standard for culverts on high traffic volume highways requires a design load with 1 in 100 year return period. It is very likely this standard was used when the culvert was built in 1960. The time of concentration of the Ross Creek watershed is approximately 6 hours, so a 6-hour rainfall with 100-year return period was evaluated in this analysis. The existing load was estimated to be $4.6m^3/s$ using the hydrological analysis methods that were recommended in the BC Supplement to TAC. These methods include the rational method, regional analysis of nearby Water Survey Canada gauging stations, and the Ministry of Environment Regional Peak Flow Map.

We evaluated the projected climate change load by assessing the relative increase in extreme 24-hour duration precipitation, as provided by PCIC, for the years 2050 and 2100. The climate model analysed the 24-hour precipitation, the total rainfall and water-equivalent snowfall accumulation within a 24-hour period, in order to provide a consistent evaluation for different infrastructure components. We assumed that the effects of climate change on snow melt and 6-hour rainfall to be the same as the 24-hour precipitation from the climate model, which shows an increase of 15.5% and 54% for the years 2050 and 2100, respectively. Climate projections indicate that future peak events will increase in frequency, but the change in magnitude is unknown. Therefore, we recommend further research on future changes to a range of rainfall durations and the subsequent effects on extreme peak flows.

We also evaluated other projected loads due to changes within the watershed. In recent years, parts of the forest in this area were affected by pine beetle infestation. Anecdotal information regarding the forest fire history for this watershed suggests that this area is vulnerable to forest fire. These factors will have short-term effects, increasing the surface runoff within the watershed before the forest grows back. Based on these considerations, we assumed there would be a 10% increased load.

5.7.2 Culvert Total Capacity

Due to lack of survey information, we made several assumptions to analyse the existing culvert capacity. We estimated some of the information by interpolating the contour lines from the 1:50,000 NTS Map. We created a hydraulic model using HydroCulv13, a culvert hydraulic analysis computer program, to find the capacity of this culvert. Results from the model show that the capacity of this culvert is between $2.2m^3/s$ and $2.5m^3/s$. This event has a return period in the order of 10 to 20 years. Also water could overtop the road surface, about 1m higher than the culvert crown, at approximately 20 to 50 year return period flow ($2.7m^3/s$ to $3.3m^3/s$). More study on this watershed will be needed to confirm these results.

The Ministry Standard requires the inlet headwater depth to culvert diameter ratio to be less than 1 ($HW/D < 1$), which implies the water level at the inlet shall not exceed the crown elevation. We performed a sensitivity analysis to confirm the order of magnitude of the analysis results. We conclude that this culvert is likely undersized and it does not meet the Ministry Standard.

The 100-year flow is an estimate based on the probability of exceeding a flood event that occurs on average once every one hundred years. Based on our results, it is possible that during the last 30 years of high flow observation, the peak flow may have exceeded the capacity of this culvert. It would be prudent to do further assessment to evaluate the actual capacity and determine if upgrade or retrofit will be required.

We assumed there would be a 5% decrease in capacity due to maturing and degradation of the culvert. Also, we assumed the culvert will be maintained regularly whenever necessary.

The numerical results and assumptions underlying this analysis are presented in **Figure 5.7** and **Figure 5.8**.

Figure 5.7: Ross Creek Culvert Engineering Vulnerability Analysis – An Example

Ross Creek Culvert & 6-hour Duration Extreme Rainfall
(m^3/s)

Total Load				
2050s	4.6	0.7	0.5	5.8
2100s	4.6	2.5	0.5	7.6
Basis for Determination	We assumed this culvert was originally designed for a 1:100 year return period. The watershed is mostly comprised of forest with an average slope of 6%. The channel slope flattens to 0.5% to 2% near the culvert, close to Endako River.	The projected climate change load for the Ross Creek watershed was assumed to be the same ratio as the extreme 24-hour duration precipitation from the climate model, which shows an increase of 15.5% and 54% for the years 2050 and 2100, respectively.	In recent year, parts of the forest in this area were affected by pine beetle infestation, which has increased the surface runoff within the watershed. The surface runoff may also increase due to logging, forest fires, land development, etc. As a result, we assumed that the load could be increased by 10%.	
Total Capacity				
2050s	2.2 to 2.5	0	0.1	2.1 to 2.4
2100s	2.2 to 2.5	0	0.1	2.1 to 2.4
Basis for Determination	Capacity of the culvert was determined by estimating the flow at which the inlet water level was at the crown elevation (HW/D = 1). Due to lack of survey information, the gradient of the culvert and channel profile were estimated by	No reduction was used for this component.	Maturing or degradation of the culverts could reduce the capacity by 5%. Maintenance will be required when the culverts are blocked by debris and whenever necessary.	

	interpolating the contour from the 1:50000 NTS Map. Sensitivity analysis was performed to confirm the magnitude of the estimated capacity.			

Figure 5.8: Ross Creek Culvert Vulnerability and Capacity Deficit Results

Ross Creek Culvert & 6-hour Duration Extreme Rainfall
(m^3/s)

Infrastructure Component	**Total Load**	**Total Capacity**	**Vulnerability**	**Capacity Deficit**
	L_T	C_T	$V_R = \frac{L_T}{C_T}$	$C_D = L_T - C_T$
2050s	5.8	2.1 to 2.4	2.4 to 2.8	3.4 to 3.7
2100s	7.6	2.1 to 2.4	3.2 to 3.6	5.2 to 5.5

5.8 *Data Sufficiency*

This analysis gives relative comparisons and is not absolute because of the nature of the available data. This analysis gives a relative ranking in broad terms and indicates areas to examine in more detail. Therefore, further study is required.

Analyzing climate data to evaluate extreme rain can be difficult as many duration and intensity event combinations can cause problems for structures. Depending on the time of concentration, storm data of various intensities (i.e. 15 min./2hrs/6hrs/etc.) are required for complete analysis. For example, 24-hour rainfall data is used as a basis for comparison to be consistent with other data parameters. This illustrates that data is required in comparable units for engineering analysis - which is the challenge when combining structure design considerations and climate forecasting.

An analysis of this type may require a more detailed study of weather and storm data, time of concentration, IDF data, structural design specification and maintenance records to determine the capacity of the existing highway drainage. This is to answer the question: if more storms are predicted then how will infrastructure perform under these changing weather conditions?

For a thorough Step 4 analysis, BC MoTI would determine if there is a built-in design reserve capacity in the current drainage structures on this particular section of the Yellowhead Highway. To accomplish this, BC MoTI may need to do a back-calculation study using a consultant to assess sections of the Yellowhead Highway to determine the original (or updated) design parameters and the actual drainage capacity to know if it would accommodate potential climate changes (similar to the Ross Creek example in Sec 5.7).

Finally, in light of the climate change prediction that snow accumulation will decrease and rainfall will increase, we are not clear on the effects of the freshet peak and rainfall induced flow. Further discussion and study may be required.

5.9 Discussion

5.9.1 Road

Road pavement asphalt cement (AC) oil grade has traditionally been chosen from historical high and low temperature ranges for the location where the highway is situated. In our study section of the Yellowhead highway, the pavement AC grade currently used is a 150/200-penetration grade, which is the equivalent to a PG 58-31 performance grade. This AC grade has a pavement surface temperature range from +58°C to -31°C.

According to climate records, the lowest air temperature in Vanderhoof was in 1984 and was -47°C. However, this was air temperature and not surface temperature and may have occurred for only one day or part of one day. Therefore, this extreme low air temperature may not have decreased the surface road temperature below its design low range of -31°C. As well, the forecast climate tells us that the low temperatures will moderate and thus less severe cold temperatures are expected in the future.

An interesting table from one of the oil companies lists the pavement grade for Prince George, just to the east of the study section of highway. This is based on the latest pavement grading system of using historical temperatures and recommends a grade of PG 52-37: giving a pavement range of +52°C to a low-end range of -37°C. It is instructive to note that this latest calculated range has a lower cold temperature but less extreme high temperature in its formulated range. So, it may be incorporating the 1984 temp of -47 into the calculation for the lower end.

However, as climate is predicted to warm, the formulated pavement grade for the upper temperature range of +58°C may be more appropriate (as is currently used). Especially since Endako temperature probe data for July 13, 2007 indicated the air temperature was 33°C and the pavement temperature was 46°C. This is a 13°C difference between the air and pavement temperatures. The future forecast highest 25-year return temperature is 41°C and the 200-year return temperature is 46°C. Therefore, if experiencing either of these temperatures in the future the pavement temperature will likely exceed the 52°C Asphalt Cement design temperature.

This highlights pavement formulation considerations given air and road temperature differentials and resulting consequences when dark coloured pavement absorbs heat thus substantially increasing its internal temperature. This observation emphasizes the importance of making correct pavement temperature choices based on future rather than historical conditions when designing pavement.

Pavement grades for varying temperature ranges can now be designed using polymer additives, at an increased cost: and in some cases this is used on BC highways. The relationship between future air temperatures and pavement surface temperatures and design specifications must be considered when identifying potential vulnerability issues.

5.9.2 Bridge

The design specifications for bridges have different temperature ranges depending on whether the superstructure is steel or concrete. Generally, steel structures have a wider temperature range design specification than concrete. This was true for the bridges on the study section of Yellowhead Highway that were built in the 1970's.

For concrete bridges in the study area, higher forecast future temperatures present a slight vulnerability based on the calculations that we assume were used when these bridges were built and the forecast temperatures developed in this study. This would be negligible on the superstructure; however it may be prudent to monitor the bearings and expansion joints during extreme temperature events.

For lower temperatures, the design standard range indicated for the Vanderhoof area is -45°C for concrete bridges, and -55°C for steel bridge structures. The most severe future forecast low temperature for 50y return is -49°C and for 200y is -55°C. So, slight design vulnerability may exist for concrete bridges according to this analysis. However, the present observed low temperature values, that are perhaps skewed by the -47°C temperature of 1984, indicate a vulnerability currently: i.e. 50-year return of -55°C and 200-year return of -62°C.

Moderating these potential vulnerabilities and capacity deficits is the lag between air temperature and the interior temperature of massive concrete members or structures. While future forecast temperatures might indicate slight vulnerability in the design temperature range of bridges, extreme high or low temperatures rarely affect the structural integrity of bridges, even outside the design specification - especially over short periods.

5.9.3 Culverts

The results from our analysis show that the vulnerability value of the Ross Creek culvert is greater than one. A potential failure condition may develop because the projected load is greater than the projected capacity. This does not mean that this culvert will definitely fail but there is a potential risk of failure at this culvert due to future changes. Adding another 1.4m culvert or replacing with a new 1.8m culvert may be necessary for the current load, as it was designed for conditions in the 1960's

Replacing the existing culvert to increase the capacity at this location may be necessary. Based on this analysis, a new 2.0m culvert will be required for year 2050 to provide adequate capacity to meet the Ministry Standard. Similarly, a new 2.2m culvert will be required for year 2100.

The new culvert sizes were estimated using the inlet control chart for CSP from the BC Supplement to TAC.

Further analysis on the vulnerability of culverts < 3m is recommended due to the uncertainties in the climate models and lack of survey information. At critical locations, it may be necessary to do a detail assessment based on the watershed settings and site conditions. Nevertheless this analysis indicates that the Ross Creek culvert, as well as some of the others from this area, may not meet the Ministry Standard due to future increased load.

Also, further assessment is recommended for the Ross Creek culvert to determine if upgrade or retrofit will be required even to handle the existing load. For future analysis, a database of the structural, hydrotechnical, and geometric information will be required.

5.9.4 Synopsis of Engineering Analysis Results

The results of the engineering analysis supported the conclusions reached through the risk assessment. The team concluded that high intensity rainfall events could overload drainage infrastructure. This is a risk profile first observed on the Coquihalla Highway Climate Change Vulnerability Assessment, although the profile appears to be somewhat attenuated on the Yellowhead Highway due to the inland location. Nonetheless, climate change forecasts anticipate higher levels of rainfall and this could present a material risk to this section of highway.

Based on these considerations the team concluded that increased rainfall intensity could require updated policies and procedures regarding design and maintenance of highway infrastructure.

The analysis of the interaction between extreme high and low temperatures and bridges indicated that the bridge design is relatively robust with respect to temperature. Calculations based on future forecast climate suggest that there might be a marginally small vulnerability to these parameters. However, the value of the indicators is so close to unity that it would be difficult to argue that this is a material level of risk. In support of this conclusion, the capacity deficit for this interaction was also marginally greater than unity. This is an area that BC MoTI may wish to monitor closely. However, there appears to be no immediate need for action on this matter.

In the past, pavement grades have been, and currently are based on historical climate data. The discussion here presents a case that it may be more prudent to consider future local climate conditions when specifying pavement grading in design standards. At least understand that future climate warming may require a higher temperature grade pavement than historical data might indicate.

The team made the following recommendations to be reviewed by BC MoTI for future retrofit or upgrade of components of this highway, and as input to inform considerations for highway design standards in general

1. To support this preliminary analysis, further investigate current design reserve capacity of the Yellowhead Highway to handle changing hydrology from increased local extreme rainfall events. Use a consultant to conduct a back-calculation study to assess sections of the Yellowhead Highway to determine the original (or updated) design parameters and the actual drainage capacity. This study would determine if the highway could accommodate potential climate change impacts resulting from higher rainfall.

2. Develop relevant, practical design parameters and guidelines to help designers account for the future influence of climate change on highway infrastructure designs. For example, it is currently difficult to account for the effect of increased magnitude and frequency of rainfall on extreme stream peak flows as it is not a linear relationship. Future hydrotechnical design may require more complex engineering such as continuous rainfall analysis and watershed modeling.

3. If, due to study findings, infrastructure components require upgrading to accommodate increased rainfall intensity, this could be accomplished as a part of regular design and maintenance activities and not as a separate program - unless a serious situation is identified (as forecast changes are 40+ years into future).

4. Further analysis on the vulnerability of culverts < 3m is recommended due to the uncertainties in the climate models and lack of survey information. At critical locations, it may be necessary to do a detailed assessment based on the watershed settings and site conditions.

5. Further assessment is recommended for the Ross Creek culvert to determine if upgrade or retrofit will be required even to handle the existing load. Highway staff note and monitor these types of situations and respond as required.

6. Require contractors to document weather conditions that caused major maintenance issues. Notionally, this would include meteorological data on rainfall, wind, etc. from the nearest weather station. This would link infrastructure problems with climate data and facilitate future monitoring of this interaction.

7. Monitor the impact of extreme temperatures on concrete bridge structures in this region. Should extreme high temperature values start to routinely exceed 35 ^{o}C, BC MoTI may need to initiate a detailed engineering study of the situation. There is no need for immediate action.

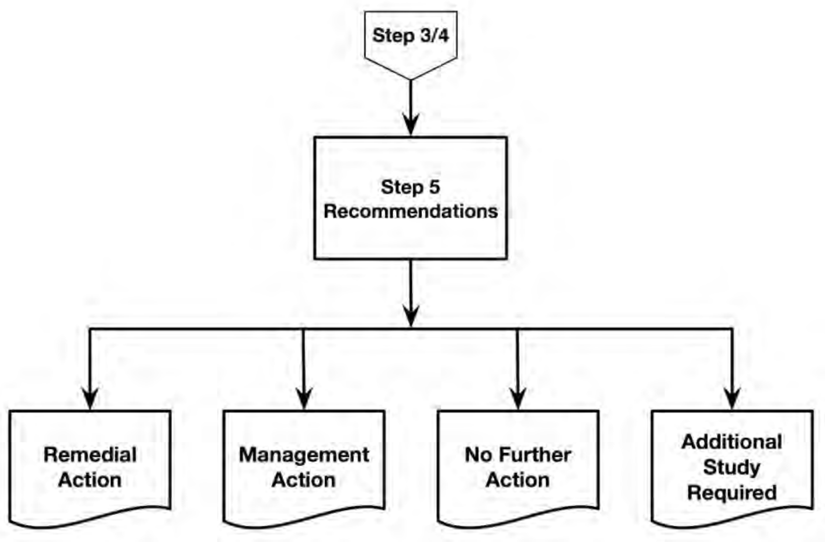
8. BC MoTI should evaluate pavement grade design and bridge design standards. It would be useful to consider future forecast climate (temperatures) for the lifespan of the structure, rather than rely on historical climate parameters such as minimum and maximum mean daily temperatures as is currently used.

6 Step 5 – Recommendations

The process flowchart for Step 5 of the Protocol is presented in **Figure 6.1**.

The completed Worksheet 5 from the Protocol is presented in **Appendix I**.

Figure 6.1: Recommendations Process Flowchart



6.1 Limitations

6.1.1 Major Assumptions

The assessment was not limited by the project definition or stated timeframe. The highway is subjected to ongoing maintenance that would tend to mitigate many of the identified climate change risks as practices typically evolve to accommodate current conditions.

6.1.2 Available Infrastructure Information

The assessment was not limited by lack of technical information regarding the highway. The team had access to personal files and very deep experience with the design, operation and maintenance of the highway.

6.1.3 Available Climate Data

Unresolved Climate Parameters

PCIC was unable to provide model-based data for the Ice / Ice Jams climate parameter during the timeframe of the study.

The risk assessment for this parameter was completed through the application of sensitivity analysis.

Visibility

The team determined that this issue requires more study to define how visibility issues arise currently on the highway. Once BC MoTI has developed a better definition of current visibility issues, they will be better placed to assess the impact of climate change on this matter.

6.1.4 Available Information on Other Change Effects

The assessment was not limited by lack of information regarding other sources of change. The experience of the team, and observations of day-to-day operation of the highway compensate for any gaps that may otherwise occur.

6.1.5 Uncertainty

Climate modeling is based on inherent assumptions regarding likely emissions scenarios. Additionally, there is a significant level of uncertainty associated with both the modeling and the analytical approaches used to downscale the information generated by the regional climate models to local conditions. PCIC addressed this concern by correlating model predictions with observed, baseline, climate conditions.

The BC MoTI team possesses a significant level of understanding of the regional climate based on many years of day-to-day, hands-on, experience with the design, operation and maintenance of the highway. This experience provided the team with sufficient foundation to assess the veracity of the climate model projections.

6.2 *Recommendations*

The recommendations arising from this risk assessment are outlined in **Figure 6.2**. These are presented for review by BC MoTI as input to inform considerations for highway design standards and any subsequent retrofit or upgrade of highway components.

Figure 6.2: Recommendations

Remedial Engineering Action	Management Action	Additional Study Required
Higher Rainfall Higher levels of anticipated rainfall present a significant risk to the infrastructure in terms of drainage management issues. These can adversely affect the safety and serviceability of the infrastructure. The infrastructure is already exhibiting vulnerability to high intensity rainfall events. Thus, the team concluded that these issues may be exacerbated by climate change and raise greater challenges to the ongoing operation and maintenance of the highway.		
1. BC MoTI should investigate current design reserve capacity of the Yellowhead Highway to handle changing hydrology from increased local extreme rainfall events. 2. If, due to study findings, infrastructure components require upgrading to accommodate increased rainfall intensity, this should be accomplished as a part of regular design and maintenance activities and not as a separate program - unless a serious situation is identified (as forecast changes are 40+ years into future).	3. BC MoTI should require contractors to document weather conditions that caused major maintenance issues. Notionally, this would include meteorological data on rainfall, wind, etc. from the nearest weather station. This would link infrastructure problems with climate data and facilitate future monitoring of this interaction. 4. Investigate if University of British Columbia (or other) infrastructure failure models contemplate climate as a variable and if this can be adapted to BC MoTI's needs.	5. Develop relevant, practical design parameters and guidelines to help designers account for the future influence of climate change on highway infrastructure designs. For example, it is currently difficult to account for the effect of increased magnitude and frequency of rainfall on extreme stream peak flows as it is not a linear relationship. Future hydrotechnical design may require more complex engineering such as continuous rainfall analysis and watershed modeling. 6. Further analysis on the vulnerability of culverts < 3m is recommended due to the uncertainties in the climate models and lack of survey information. At critical locations, it may be

Figure 6.2: Recommendations

Remedial Engineering Action	Management Action	Additional Study Required
		necessary to do a detail assessment based on the watershed settings and site conditions. 7. Further assessment is recommended for the Ross Creek culvert to determine if upgrade or retrofit will be required even to handle the existing load.
<u>Higher and Lower Temperatures</u> The analysis of the interaction between extreme high temperature and extreme low temperature and bridges indicated that bridge design on this section of highway is relatively robust with respect to temperature. Vulnerability indicators suggest that there might be a marginally small vulnerability relating to concrete bridges. However, the value of the indicators is so close to unity that it would be difficult to argue that this is a material level of risk. In support of this conclusion, the capacity deficit for these interactions was also marginally greater than unity.		
	8. BC MoTI should monitor the impact of extreme high temperature on concrete bridge structures.	9. There appears to be no immediate need for action on this matter. However, should ongoing monitoring indicate a potential problem, BC MoTI should initiate a detailed engineering study of this matter. 10. BC MoTI should evaluate pavement grade design and bridge design standards. It would be useful to consider future forecast climate (temperatures) for the lifespan of the structure, rather than rely on historical climate parameters such as minimum and maximum mean daily temperatures as

Figure 6.2: Recommendations

Remedial Engineering Action	Management Action	Additional Study Required
		is currently used.
Ice / Ice Jams PCIC was unable to provide model-based regarding ice and ice jams during the timeframe of the study.		
N/A	N/A	11. Although the team concluded that the results generated by the sensitivity analysis are relatively robust, through more advanced statistical downscaling work, BC MoTI should pursue better definition of Ice and Ice Jams
Visibility Poor visibility can lead to serious safety concerns on the highway. A large portion of serious accidents report fog as a cause. There are multiple causes of fog, including: • Very localized, from warm air over snow; • Valley fog; or • Low clouds. The team agreed that this is a potentially high-risk item and has identified this issue as a matter for further study. Ultimately, this issue may require the development of specialized highway management strategies.		
N/A	N/A	12. BC MoTI should conduct more study into visibility issues to define how these issues arise currently on the highway. 13. Once BC MoTI has developed a better definition of current visibility issues,

Figure 6.2: Recommendations

Remedial Engineering Action	Management Action	Additional Study Required
		they should assess the impact of climate change on this matter.
<u>Data Management</u> This study proved the advantage of having good data available to the assessment team. The team comprised of experts with extensive knowledge of the highway and the local climate. It would be advantageous to accumulate relevant climate and infrastructure information in a centralized location. In addition to technical design and operational data, there will be benefits from accumulating relevant climate and meteorological data in the same data room. For future assessments, the assessment team would have all relevant information immediately available. Similarly, data rooms could be established for the other highway segments contemplated for vulnerability assessment.		
N/A	14. BC MoTI should establish central repositories for technical, engineering, design, operation and climatic data necessary to conducting climate change vulnerability assessments for each highway segment contemplated for future vulnerability assessment studies.	N/A

7 Closing Remarks

7.1 *Adaptive Management Process*

BC MoTI initiated this study as the second phase of an ongoing climate change adaptive management process. Through this study BC MoTI:

- Assessed the climate change vulnerability of a portion of the Yellowhead Highway;
- Developed an understanding of their climate data needs to facilitate future assessments on this, and other, BC MoTI infrastructure;

- Refined an infrastructure component list initially developed for the Coquihalla Highway Assessment resulting in a component listing suitable for application on other BC MoTI highway vulnerability assessments;
- Refined skills and expertise in using the PIEVC assessment process;
- Identified a number of climate parameters for further study and assessment; and
- Developed a solid foundation for further vulnerability assessments on other infrastructure.

BC MoTI is presently investigating the possibility of another stage of this process of assessing BC highway infrastructure, as resources allow, using the PIEVC process.

BC MoTI conducted this assessment using internal resources as well as the expertise of the Pacific Climate Impact Consortium, with facilitation by Nodelcorp Consulting Inc. The result of the approach is to understand climate change vulnerability using an assessment tool (PIEVC); and how this understanding can be integrated into the general understanding of staff responsible for the highway infrastructure and imbedded into day-to-day design, management and operations activity.

As part of their ongoing work on climate change adaptation, BC MoTI has established an exemplary working relationship with the Pacific Climate Impacts Consortium at the University of Victoria. Through this relationship, climate parameters and data requirements have been refined to support further vulnerability assessment work. Also, these studies enable understanding of climate implications for BC MoTI to consider in future studies to lead to improved design standards and safer highway infrastructure.

7.2 *Comparison with Coquihalla Highway Vulnerability Assessment*

The Yellowhead Highway assessment was the second of a series of highway infrastructure climate change vulnerability assessments conducted by BC MoTI. The first assessment was on the Coquihalla Highway.

This particular section of the Yellowhead Highway was selected for this assessment because of the significant differences between the two highway infrastructures' geographic and climatological locations.

The Coquihalla Highway is located in mountainous terrain. The Coquihalla River or tributaries run alongside the length of the highway infrastructure with a significant road elevation change of approximately 900 meters from the start point to the end point. There is significant climatological gradient, especially at the top end of this section of road. This can lead to dramatic differences in the climatic conditions experienced over a few kilometres of the highway.

In contrast, the Yellowhead Highway runs from the eastern border with Alberta west through the Cariboo Mountains to Prince George, and through the Fraser Plateau, the Bulkley River Valley and the Skeena River Valley, before reaching the west coast at Prince Rupert. There is no significant climatological gradient in the region of the study, the area being generally in a plateau region.

The Coquihalla Highway is more exposed to Pacific weather systems, such as the Pineapple Express, which played a significant role in the overall risk profile. The highway was found to be very sensitive to drainage issues and exhibited a large number of high-risk interactions related to extreme rainfall events.

The climate in the region of the Yellowhead highway is somewhat attenuated by its inland location. As a result, the infrastructure risk profile presents a lower level of overall risk, with no identified high-risk interactions. Nonetheless, the highway did exhibit sensitivity to anticipated higher levels of rainfall resulting in some heightened risk associated with highway drainage.

Although the risk profile for the Yellowhead Highway was determined to be lower than the Coquihalla Highway, the issues that drive the risk were found to be quite similar – higher overall anticipated levels of precipitation.

8 Conclusion

Based on this risk assessment, the Yellowhead Highway is generally resilient to climate change. The highway will experience a somewhat higher risk profile with regard to high rainfall events, but none of these interactions fall into a high-risk rating.

The risk assessment did not identify any new risks for the BC MoTI team to consider. Rather, the process allowed the team to define, review, and document their risk assessment deliberations. Although there were no surprises, the team was able to substantiate their view of the highway's risk profile through experience, climate model data and sensitivity analysis. Ultimately, this combination of analytical steps allowed BC MoTI to establish a robust risk profile for the highway.

9 Appendices

Appendix A	PIEVC Engineering Protocol for Climate Change Infrastructure Vulnerability Assessment
Appendix B	Site Selection Criteria
Appendix C	Completed Protocol Worksheet 1
Appendix D	Completed Protocol Worksheet 2
Appendix E	Pacific Climate Impacts Consortium Summary Report
Appendix F	Completed Protocol Worksheet 3
Appendix G	Sensitivity Analysis
Appendix H	Completed Protocol Worksheet 4
Appendix I	Completed Protocol Worksheet 5
Appendix J	List of Workshop Attendees

Appendix A

PIEVC Engineering Protocol for Climate Change Infrastructure Vulnerability Assessment

Part I

PIEVC Engineering Protocol for Climate Change Infrastructure Vulnerability Assessment

Part I

April 2009

For further information about this ***Engineering Protocol*** or the ***National Engineering Vulnerability Assessment*** **Project** please contact the PIEVC Secretariat at Engineers Canada:

David Lapp, P.Eng.
Manager, Professional Practice
Engineers Canada

1100-180 Elgin Street
Ottawa, Ontario, Canada
K2P 2K3

david.lapp@engineerscanada.ca

(613) 232-2474 Ext. 240

Table of Contents

Part I – Background, Overview and Guidance

List of Figures

Part I – Background, Overview and Guidance

1 Introduction and Scope

This document is intended to guide practitioners through the ***PIEVC Engineering Protocol for Climate Change Infrastructure Vulnerability Assessment*** (the Protocol). The Protocol is a step-by-step process to assess the impact of climate change on infrastructure. Information developed through this assessment process will assist owners and operators to effectively incorporate climate change adaptation into design, development and management of their existing and planned infrastructure. This protocol has been successfully utilized to assess four categories of infrastructure:

1. Buildings
2. Roads and associated structures
    - Culverts
    - Surface
    - Bridges
    - Etc.
3. Stormwater and wastewater treatment and collection systems
4. Water resource systems and other water management infrastructures
    - Potable water collection
    - Treatment and distribution
    - Water control dams
    - Retention and flood control structures
    - Etc.

The Protocol describes a step-by-step process of risk assessment and engineering analysis for evaluating the impact of climate change on infrastructure. The observations, conclusions and recommendations derived from the application of this protocol provide a framework to support effective decision-making about infrastructure operation, maintenance, planning and development.

This Protocol has been developed for owners and operators to assess public infrastructure. However, the principles and steps will be similar for assessing privately owned infrastructure.

The Protocol was developed with funding contributions from Natural Resources Canada. Engineers Canada (the business name of the Canadian Council of Professional Engineers) owns the intellectual property that is the Protocol. It may be used in Canada for Canadian-based infrastructure without charge, provided the user signs a license agreement with Engineers Canada. The Protocol may be used internationally for infrastructures located outside Canada subject to the payment of a license fee and a license agreement with Engineers Canada.

The Public Infrastructure Engineering Vulnerability Committee (PIEVC) is a national steering committee set up by Engineers Canada in 2005. This committee consists of senior representatives from Federal, provincial and municipal levels of government in Canada along with several non-government organizations. It oversees the National Engineering Vulnerability Assessment project, a long term initiative of the Canadian engineering profession to assess the vulnerability of public infrastructures to the impacts of future changes in climate. This information is a vital input to propose adjustments and amendments to infrastructure codes and standards and related engineering practices.

Note that Engineers Canada provides the Secretariat for the PIEVC and is responsible for all legal and administrative agreements relating to the use of the Protocol.

PIEVC is supported by infrastructure Expert Working Groups consisting of engineers and other technical experts with design and operations experience in the particular infrastructure category as well as climate scientists and other subject matter experts. PIEVC currently has four such groups as follows:

1. Buildings
2. Roads and associated structures
3. Stormwater and wastewater systems
4. Water resource management systems

This document is divided into three main sections:

1. Description of the processes and organization for planning engineering vulnerability assessments of public infrastructure
2. Presentation of the basic principles of risk management that are applicable to this work, along with technical references
3. Procedural description of the five steps involved in executing the Protocol.

The document includes worksheets to record the work completed at each step.

2 Vulnerability Assessment Planning and Execution

Engineering vulnerability assessments normally involve one or, at most, a few individual infrastructures rather than an entire inventory. The individual infrastructure(s) should be carefully selected to provide a representative sample of the inventory. If significant vulnerabilities are detected, and there is widespread variability in nature and severity of vulnerabilities, it may be necessary to assess all individual infrastructures in an inventory to determine what adaptive actions are required for an individual infrastructure.

PIEVC has developed a five-phase process for planning and executing vulnerability assessments, including:

- Phase I – Initial Contact and Preliminary Discussions
- Phase II – Project Scoping and License Agreement
- Phase III – Procurement of Expertise

- Phase IV – Engineering Vulnerability Assessment
- Phase V – Conclusions and Recommendations

These phases are briefly described in the following sections and are presented graphically in Figure 1.

Note that the engineering vulnerability assessment of an individual infrastructure or group of infrastructures is referred to as the “Project” for the remainder of this document.

2.2 *Phase I - Initial Contact and Preliminary Discussions*

Discussion for a Project may be initiated in a number of ways:

- The PIEVC Secretariat approaches an owner or operator or their representative (the “Project Partner”) and negotiate a Project. The Project Partner may be represented on one of PIEVC’s various committees or may be approached due to some unique features of the infrastructure or its location;

- A potential Project Partner may approach PIEVC with a unsolicited proposal;

- The PIEVC Secretariat issues a Request for Expression of Interest to infrastructure owners, soliciting their interest in a Project; or

- Consultants may identify potential infrastructure assessment sites and approach the infrastructure owner and the PIEVC Secretariat with an unsolicited proposal.

The Protocol is the intellectual property of Engineers Canada, and owners/operators of infrastructure, as well as third-party users, (e.g. consultants) may not use it without the permission of Engineers Canada, which is normally granted through the signing of a license agreement. Part of this agreement includes the obligation to share the results of the assessment with the Federal Government of Canada, PIEVC and Engineers Canada.

2.3 *Phase II - Project Scoping*

Once the potential Project Partner confirms their serious intent to pursue an assessment, the Project enters the Project Scoping and License Agreement phase. During this phase, the project partner and the PIEVC Secretariat:

- Complete the initial stages of the project definition in sufficient detail to complete a project work statement suitable for procurement purposes
- Negotiate and sign a License Agreement between Engineers Canada and the Project Partner;
- Negotiate a memorandum of agreement (MOA) that outlines the roles and

responsibilities of Engineers Canada and the Project Partner, as well as terms and conditions that will govern the Project. It includes the License Agreement and may include additional sections that cover any financial obligations between or among the signing parties as well as any additional administrative policies and procedures needed to execute the agreement;

- Normally an outside consultant is required, and arrangements for procuring these services utilize the procurement policies and procedures of the Project Partner which may include the development of a Request for Proposal (RFP) for cases where a competitive process is required or desired.

The PIEVC Secretariat has generic versions of MOAs, works statements, and RFPs that can help guide this process. These are available through the Secretariat. However, every infrastructure owner has unique management and technical circumstances that may affect the terms and conditions that will guide this process.

Detailed instructions for developing a project definition are integral to this Engineering Protocol and are outlined in Section 8.1 of this document. Project proponents are encouraged to use these procedures and the related worksheets provided under separate cover to guide the project definition process. Obviously, at the project scoping stage, project proponents will not have access to all of the data necessary to complete this step of the engineering protocol. However, the methodology and underlying thought process will significantly aid the project proponent to identify the key components that must be incorporated in the project Work Statement to provide potential consultants with sufficient information to appropriately scope and cost the engineering assessment.

Normally, at the completion of Project Scoping PIEVC and the infrastructure owner will have developed and agreed to three key documents:

1. A Memorandum of Agreement;
2. A Project Work Statement: and
3. A Request for Proposal.

These documents along with this Engineering Protocol will guide the rest of the assessment process.

PIEVC is aware that other project management alternatives may be more suitable in some circumstances. However, in every case the project proponent and PIEVC must clearly articulate the project definition and delineate management responsibilities. In some circumstances the project management tools may differ slightly from those outlined above but the process must always result in similar management system controls for the project.

2.4 *Phase III - Procurement of Expertise*

Normally, the Project partner will manage the procurement of expertise according to their own policies and procedures.

The RFP developed in Phase II will be used to guide the technical requirements of the process.

During this stage, the PIEVC Secretariat will normally facilitate the formation of a Project Advisory Group consisting of representatives from the:

- Infrastructure owner;
- PIEVC Secretariat;
- Corresponding PIEVC Expert Working Group; and
- Other groups, as appropriate.

One of the roles of the Project Advisory Group is to assist in the evaluation of proposals and to advise the Project Partner that the technical requirements of the work are met and the project team has the requisite mix of expertise and experience to satisfy the requirements.

Representatives from the project oversight group may assist the infrastructure owner evaluate proposal documents.

In some circumstances the Project Partner may deem it appropriate to sole-source the project to a specific consultant. The PIEVC Secretariat and Engineers Canada have no objection to this approach provided that any sole-source contract meets the project management guidelines of the infrastructure owner and written justification is provided to the PIEVC Secretariat.

It is recommended that the Project Partner negotiate a consultant agreement incorporating the Work Statement developed during Phase II.

2.5 Phase IV - Vulnerability Assessment

The PIEVC Engineering Protocol will guide the vulnerability assessment. The protocol is detailed in Sections 3 and 4.

The consultant will provide three key deliverables.

1. Prior to initiating detailed work, it is strongly recommended that the consultant provide an engagement plan outlining their key deliverables, schedule, personnel and management controls governing the vulnerability assessment.
2. Each month, the consultant will provide a written progress report.
3. At project completion the consultant will provide a detailed project report outlining conclusions on the nature and severity of the findings, conclusions on the nature and severity of infrastructure component vulnerabilities and recommendations.

The approved project Work Statement may also identify other key deliverables specific to the particular infrastructure owner or PIEVC needs.

On a regular basis, the consultant will convene a project update teleconference/meeting including the PIEVC project oversight committee.

2.6 Phase V - Conclusions and Recommendations

At the completion of the vulnerability assessment the consultant will provide a set of conclusions and recommendations relating to the climate impact and adaptation of the infrastructure. These conclusions and recommendations will fall into several categories, as outlined in Section 4.5:

1. A report of infrastructure components that have been assessed to be vulnerable.

2. Initial recommendations regarding possible:
    i. Remedial engineering actions;
    ii. Monitoring of structure over a set time period;
    iii. Management actions;
    iv. Additional data collection; or
    v. Additional engineering analysis of particular infrastructure components that may be necessary to determine extent and nature of vulnerabilities.

3. A report on the infrastructure components that have been assessed to have sufficient adaptive capacity to withstand projected climate change impacts; thus requiring no further action at this time.

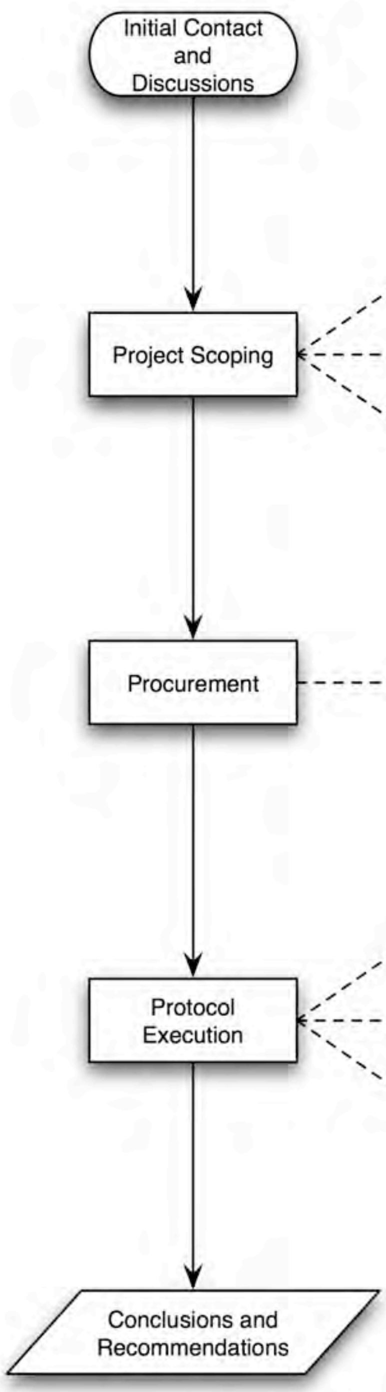
4. A report on data gaps and availability; requiring additional work or studies.

5. Identification of infrastructure components that may be evaluated in the future.

6. A report on other conclusions, trends, insights and limitations.

As part of any License Agreement with Engineers Canada, the Project Partner will forward a copy of the report, including the conclusions and recommendations to Engineers Canada. The findings will be synthesized and incorporated within a ***National Engineering Vulnerability Registry*** that is managed by Engineers Canada. The registry is used to sort, consolidate and analyze engineering vulnerabilities in the four infrastructure categories at the component level.

Figure 1: Overall Project Execution Process



3 Protocol Overview

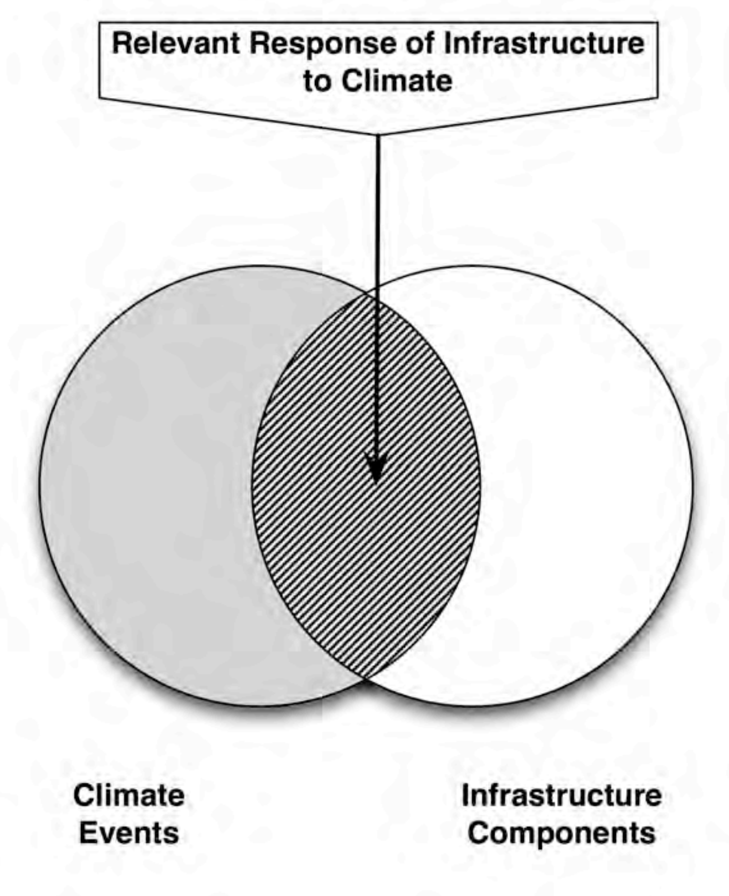
Climate data is used to design infrastructure. Under climate change, historic data may no longer be appropriate. As a result, infrastructure may be vulnerable. Existing infrastructure may not have sufficient resiliency. New infrastructure may not be designed with sufficient load and adaptive capacity.

To assess climate change infrastructure vulnerability, the practitioner must evaluate:

1. The infrastructure;
2. The climate (historic, recent and projected); and
3. Historic and forecast responses of the infrastructure to the climate.

This interaction is depicted in Figure 2.

Figure 2: Venn Diagram Illustrating Relevant Interactions between Climate and Infrastructure



A great deal of information may be available to describe the infrastructure and the climate in the region. The protocol sets out a procedure to sift the data to develop an understanding of how climate and infrastructure interact to create vulnerability. Not *all* climate and infrastructure data is necessary to complete the protocol. The initial stages of the protocol help the practitioner identify the *key* data necessary to complete the assessment. Throughout the protocol the practitioner is directed to continuously evaluate the availability and quality of data sufficient to support conclusions and recommendations.

The protocol is divided into five steps, as illustrated in Figure 3. Each step of the protocol is described in greater detail in Sections 3.1 through 3.5.

Figure 3: Overview of the Protocol

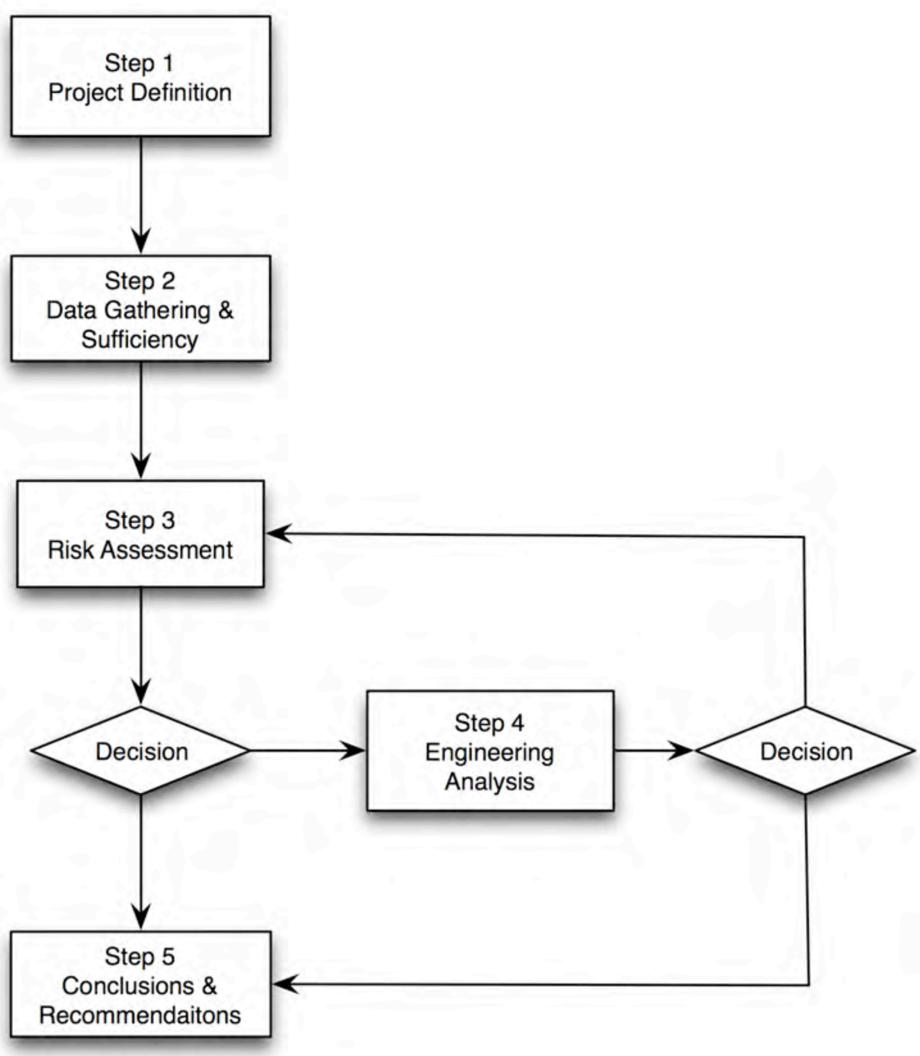
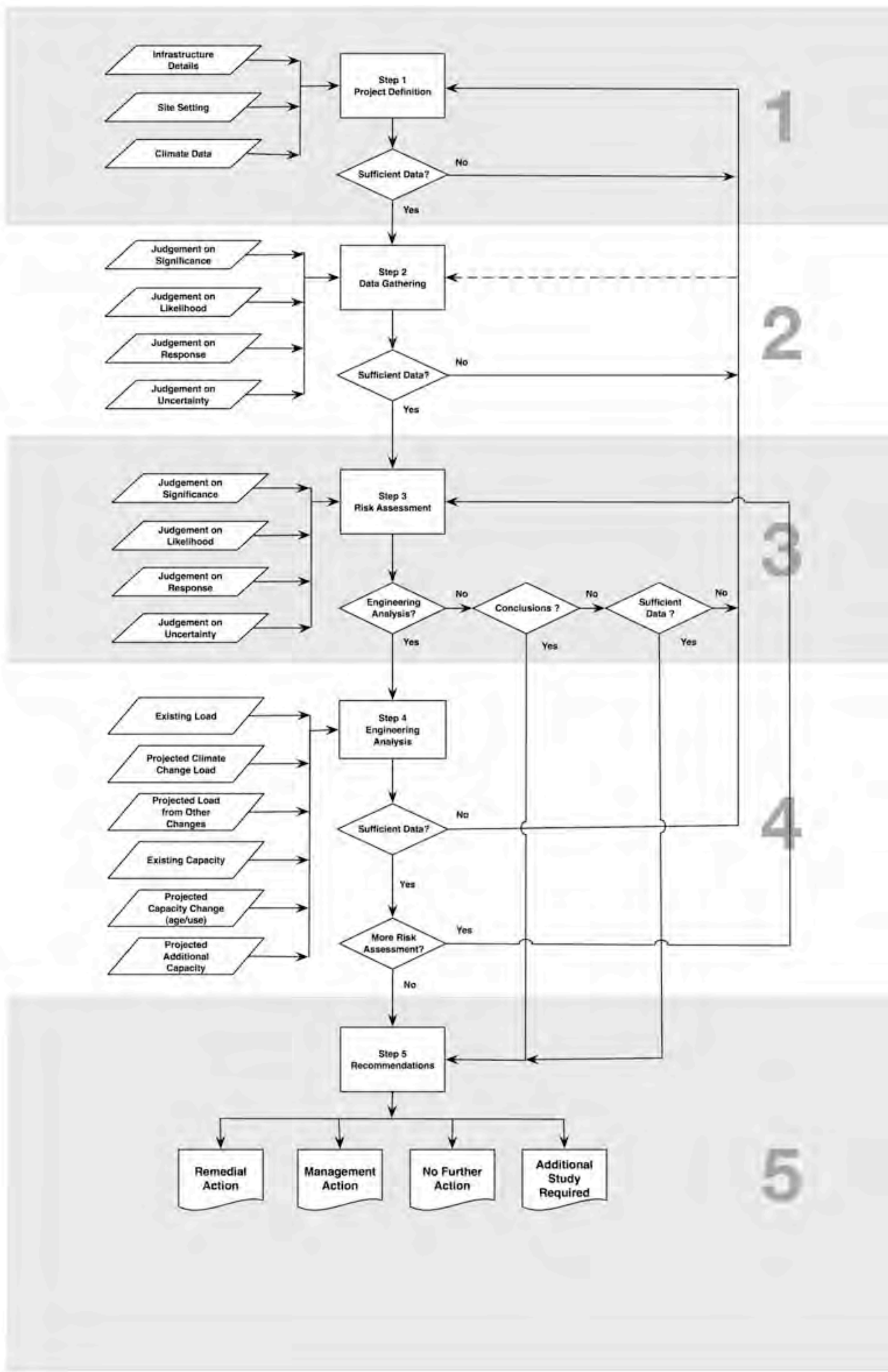


Figure 4 outlines the detailed protocol procedure. Part II of this protocol expands on this flow chart and provides specific procedures for conducting an engineering climate change infrastructure vulnerability assessment. At the completion of each step of the protocol the practitioner is required to assess data sufficiency and address the need for further, more detailed, analysis. This results in a number of feedback loops within the protocol and significant inter-linkage between steps. The detailed protocol provides guidance on how to answer these questions. However, the practitioner must take care to fully evaluate, and document, each of these key decision points to manage against scope creep and avoid iterations, unless completely justified within the context of the assessment. As general guidance, the practitioner should consider the incremental benefit gained by additional costs of data acquisition or technical analysis. This is a project specific assessment driven by budget, risk and other management factors. If the practitioner is unsure of any of these factors, they are encouraged to work with the Project Partner to ensure that all relevant factors are considered.

Figure 4: Detailed Protocol Flow Chart



3.1 Step 1 - Project Definition

In Step 1 the practitioner will be asked to:

- Develop a general description of:
    - The infrastructure;
    - The location;
    - Historic climate;
    - Load;
    - Age;
    - Other relevant factors; and
- Identify major documents and information sources.

In this step the practitioner defines the boundary conditions for the vulnerability assessment.

3.2 Step 2 - Data Gathering and Sufficiency

In Step 2 the practitioner will be asked to provide more definition about:

1. Which parts of the infrastructure will be assessed; and
2. The particular climate factors that will be considered.

Step 2 is comprised of two key activities:

1. Identification of the features of the infrastructure that will be considered in the assessment:

    - Physical elements of the infrastructure;
        - Number of physical elements;
        - Location(s);
    - Other relevant engineering/technical considerations:
        - Material of construction;
        - Age;
        - Importance within the region;
        - Physical condition;
    - Operations and maintenance practices;
    - Operation and management of the infrastructure;
        - Insurance considerations;
        - Policies;
        - Guidelines;
        - Regulations; and
        - Legal considerations.

2. Identification of applicable climate information. Sources of climate information include, but are not limited to:

- The National Building Code of Canada, Appendix C, Climate Information;
- Intensity - Duration – Frequency (IDF) curves;
- Flood plain mapping;
- Regionally specific climatic modeling;
- Heat units (i.e. degree-days) (i.e. for agriculture, HVAC, energy use, etc.); and
- Others, as appropriate.

The practitioner will be required to exercise professional judgement based on experience and training. Step 2 is an interdisciplinary process requiring engineering, climatological, operations, maintenance, and management expertise. The practitioner must ensure that the right combination of expertise is represented either on the assessment team or through consultations with other professionals during the execution of the assessment.

3.3 *Step 3 - Risk Assessment*

In Step 3 the practitioner will identify the interactions between the infrastructure, the climate and other factors that could lead to vulnerability. These include:

- Specific infrastructure components;
- Specific climate change parameter values; and
- Specific performance goals.

The protocol requires the practitioner to identify which elements of the infrastructure are likely to be sensitive to changes in particular climate parameters. They will be required to evaluate this sensitivity in the context of the performance expectations and other demands that are placed on the infrastructure. Infrastructure performance may be influenced by a variety of factors and the protocol directs the practitioner to consider the overall environment that encompasses the infrastructure.

At this point in the protocol the practitioner, in consultation with the Project Partner, management, engineering and operation personnel, will perform a risk assessment of the infrastructure's vulnerability to climate change. The interactions identified will be evaluated based on the professional judgement of the assessment team. The risk assessment will identify areas of key concern.

The practitioner will identify those interactions that need further evaluation. The assessment process does not require that all interactions be subjected to further assessment. In fact, in most assessments most of the interactions considered will ultimately be eliminated from further consideration. Some interactions may clearly present no, or negligible, risk. Some interactions may clearly indicate a high risk and a need for immediate action. Those interactions that do not yield a clear answer regarding vulnerability may be subjected to the further Engineering Analysis as outlined in Section 8.4.

At this stage, the practitioner must also assess data availability and quality. If professional judgment identifies a potential vulnerability that requires data that is not available to the assessment team, the protocol requires that the practitioner revisit Step 1 and/or Step 2 to acquire and refine the data to a level sufficient for risk assessment and/or engineering analysis. The practitioner may determine that this process requires additional work outside of the scope of the assessment. Such a finding must be identified in the recommendations outlined in Step 5.

This is a key decision point in the Protocol. The practitioner is required to determine:

- Which interactions require additional assessment;
- Where data refinement is required; and
- Initial recommendations about:
  - New research;
  - Immediate remedial action; or
  - Non-vulnerable infrastructure.

3.4 Step 4 - Engineering Analysis

In Step 4 the practitioner will conduct focused engineering analysis on the interactions requiring further assessment, as identified in Step 3.

The protocol sets out equations that direct the practitioner to numerically assess:

- The total load on the infrastructure, comprising:
  - The current load on the infrastructure;
  - Projected change in load arising from climate change effects on the infrastructure;
  - Projected change in load arising from other change effects on the infrastructure;

- The total capacity of the infrastructure, comprising:
  - The existing capacity;
  - Projected change in capacity arising from aging/use of the infrastructure; and
  - Other factors that may affect the capacity of the infrastructure.

Based on the numerical analysis:

- A vulnerability exists when ***Total Projected Load*** exceeds ***Total Projected Capacity***; and
- Adaptive capacity exists when ***Total Projected Load*** is less than ***Total Projected Capacity.***

At this stage the practitioner must make one final assessment about data availability and quality. If, in the professional judgement of the practitioner, the data quality or statistical error does not support clear conclusions from the Engineering Analysis, the protocol directs the practitioner to revisit Step 1 and/or Step 2 to acquire and refine the data to a level sufficient for robust engineering analysis. The practitioner may determine that this process requires additional work outside of the scope of the assessment. Such a finding must be identified in the recommendations outlined in Step 5.

Once the practitioner has established sufficient confidence in the results of the engineering analysis, the protocol reaches another key decision point. The practitioner must decide to either:

- Make recommendations based on their analysis (Step 5); or
- Revisit the risk assessment process based on the new/refined data developed in the engineering analysis (Step 3).

3.5 *Step 5 - Recommendations*

In Step 5 the practitioner is directed to provide recommendations based on the work completed in Steps 1 through 4. Generally, the recommendations will fall into five major categories:

- Remedial action is required to upgrade the infrastructure;
- Management action is required to account for changes in the infrastructure capacity;
- Continue to monitor performance of infrastructure and re-evaluate at a later time;
- No further action is required; and/or
- There are gaps in data availability or data quality that require further work.

The practitioner may identify additional conclusions or recommendations regarding the veracity of the assessment, the need for further work or areas that were excluded from the current assessment.

4 The Team

4.2 *A Multi-Disciplinary Team*

When guided by a well-balanced team of qualified professionals, the protocol is a very powerful tool, derived from standard risk management methodologies, tailored to climate change. It is quite common for practitioners to identify data gaps, poor data quality, or lack of relevant tools such as local results from regional climatic models. Often, lack of financial resources or project schedule commitments can affect the ability of the practitioner to completely address these concerns. The protocol allows a number of avenues to proceed when these issues arise. For example,

- The practitioner may identify the data gap and make a recommendation for further work outside of the context of the vulnerability assessment.
- The practitioner may identify the data gap and table any further analysis on the affected parameters.

- The practitioner may infill the missing data based on reasonable professional assumptions and precede with the analysis.

Lack of input data need not deter practitioners from making professionally based judgments and expressing opinions leading to recommendations.

Of paramount importance in addressing the types of questions raised by the protocol is a well-balanced team of professionals dedicated to the execution of the vulnerability assessment. The correct blend of professional and local expertise can support and validate assumptions that allow the practitioner to compensate for missing or poor quality data and account for the lack of other technical resources. Team composition and depth of experience has a very significant bearing on the veracity of the final assessment report. The following expertise is absolutely necessary on the assessment team:

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

We cannot overstate the importance of local knowledge in conducting a vulnerability assessment. Local knowledge, filtered through the overall expertise of the assessment team, more often than not, will compensate for data gaps and provide a solid basis for professional judgment of the vulnerability of the infrastructure.

Throughout this protocol we use the term practitioner. The reader should interpret this to mean the entire assessment team. It is highly unlikely that a project proponent will identify a practitioner with all of the necessary attributes, skills, knowledge and experience in a single person.

4.3 *The Team Leader*

The team leader should be an experienced professional with demonstrated experience in management of multi-disciplinary projects. In some cases, the team leader may also contribute some of the other technical and professional skills outlined above. However, in all cases the leader must be able to coordinate and prioritize the work of the rest of the team and have sufficient background and experience to consolidate findings from different disciplines and areas of expertise. These attributes are normally developed over years of professional practice. Thus, it is generally inadvisable to assign team leadership to a junior professional.

5 Fundamentals of Risk and Risk Assessment

This PIEVC Engineering Vulnerability Protocol is derived from standard risk assessment processes. As such, there is some advantage to reviewing these concepts prior to initiating a vulnerability assessment to ensure that the entire team and workshop participants have a common understanding of the expectations established by the protocol and of acceptable approaches for addressing questions that the practitioner may identify throughout the exercise.

Risk is defined as the possibility of injury, loss or negative environmental impact created by a hazard. The significance of risk is a function of the *probability* of an unwanted incident and the *severity* of its consequence[1]. In mathematical terms:

$$R = P \times S$$

Where:

R = Risk
P = Probability of a negative event
S = Severity of the event, given that it has happened

In risk assessment, practitioners answer three questions[2]:

1. What can happen?
2. How likely is it to happen?
3. Given that it has happened, what are the consequences?

The PIEVC Protocol guides the practitioner through a process designed to answer these questions.

In risk analysis, practitioners are cautioned to ensure that their assessment of probability does not affect their assessment of severity. Basically, the consequence of an event is independent from the likelihood that the event will occur. By separating probability and severity in this way, the practitioner is able to dissect the factors that contribute to risk. Ultimately, this can yield very useful information to guide recommendations regarding approaches to risk mitigation. Practitioners can identify steps that reduce:

- The probability of an event;
- The severity of an event; or
- Both.

[1] Paul R. Amyotte, P.Eng. & Douglas J. McCutcheon, P.Eng.; ***Risk Management – An Area Of Knowledge For All Engineers***; Engineers Canada, 2006
[2] Tim Bedford and Roger Cooke; ***Probabilistic Risk analysis: Foundations and Methods***; Cambridge University Press; Fourth Printing 2006

5.2 *Hazard Identification – What can happen?*

In this protocol, hazards are identified as interactions between identified climatic events and components of the infrastructure. The practitioner identifies conceivable climatic events that could occur in the region within the timeframe of the vulnerability assessment.

For example, the practitioner could identify that an event of 50 mm of rain in one hour is conceivable during the remaining service life of the infrastructure.

The practitioner will then review the infrastructure and determine the components and sub-components that comprise the infrastructure. This requires professional judgement. If the component analysis is not sufficiently detailed, the assessment may miss potential vulnerabilities. However, if the component analysis is overly detailed, the scope of the assessment can mushroom and become unmanageable or very expensive.

Once the component analysis and climate analysis are completed the practitioner consolidates the lists. The consolidated list yields a set of interactions between climatic events and infrastructure components.

For example, the list may suggest that, during the timeframe of the evaluation, it is conceivable that the 50 mm rain event could impact culverts within the infrastructure system.

As a final step of the hazard identification the practitioner normally will perform a pre-screening of the identified interactions. In essence, they will judge if the identified interactions could conceivably occur. It is imperative that at this stage the assessment the practitioner does not establish a numerical value for the likelihood of the interaction. In essence, they are assessing the reasonableness or conceivability of the interaction. Based on professional judgment, this "sniff test" can significantly reduce the number of interactions considered in further evaluation.

At the end of the hazard analysis, the protocol will yield a set of interactions, or hazards, that will be assessed further for likelihood and severity, finally yielding a value for risk.

Hazard analysis does not identify risks.

Hazard analysis identifies a specific set of circumstances that could potentially result in a negative outcome. In the following analysis, the practitioner will establish just how likely the interaction is and the consequences of the interaction, should it actually occur.

5.3 Probability – How likely is it to happen?

To determine risk, the practitioner must first assign a probability of an interaction occurring. In some circumstances, historical data or statistics are available to guide this assessment. However, more often than not, this guidance is not available. In such cases, the probability can be assigned based on professional judgment. This is a normal procedure in risk assessment. Thus, the lack of measured data should not impose an impediment to completing the vulnerability assessment. Standard risk assessment textbooks state:

> ***Expert judgment techniques are useful for quantifying models in situations in which, because of either cost, technical difficulties or the uniqueness of the situation under study, it has been impossible to make enough observations to quantify the model with "real data".***[2]

This protocol addresses this issue through guidance regarding:

- The composition of the practitioner team; and
- The participants at the Vulnerability Assessment Workshop.

It is important to ensure that sufficient expertise, experience and knowledge be accessed to ensure a balanced and reliable estimate of the probability.

In the Vulnerability Assessment Workshop, participants systematically assess each of the interactions deemed to be conceivable and reasonable by the practitioner. The combined expertise and experience of the workshop participants is designed to yield a pragmatic and realistic estimate of the probability of occurrence of an infrastructure – climate event interaction.

The protocol provides guidance regarding the selection of probability values. The protocol uses a standardized probability scale of 0 to 7, where 0 means that the event will never occur and 7 means that the event is certain. Further, the protocol provides three different approaches to assigning these factors. Finally, the protocol allows the practitioner to use other methods to assess probability, should these methodologies be justified given the circumstances of the current assessment.

5.4 Severity – Given that it has happened, what are the consequences?

The second step in establishing a value for risk is to assess the consequences of an event, given that the event has happened. In some circumstances, historical data or statistics are available to guide this assessment. However, more often than not, this guidance is not available. In such cases, the severity can be assigned based on professional judgment.

It is important to ensure that sufficient expertise, experience and knowledge be accessed to ensure a balanced and reliable estimate of the severity.

In the Vulnerability Assessment Workshop, participants systematically assess each of the interactions deemed to be conceivable and reasonable by the practitioner. The combined expertise and experience of the workshop participants is designed to yield a pragmatic and realistic estimate of the severity of an infrastructure – climate event interaction, should that event ever occur.

The protocol provides guidance regarding the selection of severity values. The protocol uses a standardized severity scale of 0 to 7, where 0 means no negative consequences, should the interaction occur and 7 means significant failure, should the interaction occur. Further, the protocol provides two different approaches to assigning these factors. Finally, the protocol allows the practitioner to use other methods to assess severity, should these methodologies be justified given the circumstances of the current assessment.

5.5 ***Risk – What is the significance of the event?***

Finally, the practitioner is directed to determine the risk for each interaction. As previously stated, risk is a function of the *probability* of an unwanted incident and the *severity* of its consequence. Logistically, the protocol directs the practitioner to multiply the probability and severity values derived above to establish a value for risk. If the practitioner uses the recommended probability and severity scales, the risk analysis will yield a set of risk values ranging between 0 and 49. Since, the scale factors are unitless, the resulting risk values are also unitless.

The protocol then goes on to help the practitioner define criteria for further screening the risks. Low risk interactions are eliminated from further evaluation. Medium risk interactions are normally subjected to further engineering analysis (Step 4 of the Protocol). High risk interactions are normally passed forward to conclusions and recommendations (Step 5 of the Protocol).

In simple terms, low risk interactions pose minimal threat. Medium risk interactions ***MAY*** be significant and require further refinement and analysis before the practitioner passes final judgement. High risk interactions pose a material threat and require remedial action. The protocol identifies categories of recommendations for high risk items including, but not limited to, management action, retirement, or re-engineering and retrofit.

The concept of tolerance to risk is inherent in the predefined cut-offs identified by the protocol. Basically, the protocol assumes that infrastructure owner accepts a level of risk simply by operating the infrastructure. The owner accepts this level of risk as a normal consequence of the operation and may already have procedures in place to manage the risk. In essence, no activity is risk free, but a minimal level of risk is acceptable. The protocol also assumes that as risk values increase, the owner's tolerance to the risk decreases and they are likely to undertake risk mitigation activities to address the concern and reduce the risk to a level within their risk tolerance. At the highest level, the risk exceeds the boundaries of the owner's risk tolerance and they will take urgent action. The protocol allows the practitioner to adjust the cut-off values, as appropriate, based on their professional judgment and consultation with the infrastructure owner.

5.6 *Common Myths and Misconceptions About Risk*

It is important for practitioners to understand the implications of common myths and misconceptions about risk. In this protocol, there is a significant level of involvement with laypeople. Understandably, the average layperson does not have a profound technical understanding of risk. Thus, the practitioner has the responsibility to guide the layperson through the process in a technically rigorous manner.

It is important to be able to identify and address the most common problems associated with risk analysis. Some of these common myths and misconceptions include:

> ***"Hazard is risk."*** It is very common for the average person to confuse the conceivability of an event with its risk. Simply because an event can be conceived does not mean that, in the real world, it will actually occur. Risk assessment considers the likelihood of an event in association with its consequence. Hazard assessment simply asks the question: "What events can I imagine that could result in a negative outcome."
>
> ***"Probability is risk."*** Often the average person will confuse the likelihood of an event with risk. Likelihood, or probability, is only one factor that constitutes risk. The severity of the event, should it occur, must also be considered. When probability is confused with risk, the impact of the event is neglected. It is possible to label high probability - low impact events as high risk. This can lead to unnecessary management action. Conversely, it is possible to label high severity – low probability events as low risk, resulting in little or no mitigative action.
>
> ***"Severity is risk."*** The average person may confuse the severity of an event with its risk. In this scenario, high severity events are considered to be high risk regardless of their likelihood. Similarly, low severity events are considered to be low risk even though they may occur quite frequently. As above, by neglecting one key factor of risk the actual risk may not be properly assessed or managed.
>
> ***"Probability and severity are dependent (linked) variables."*** This misconception is often the most difficult to address with a layperson. It is very challenging for the average person to separate the likelihood of an event from its consequences. For example, if they can conceive of the event, then it must be serious. The problem with this view is that it does not allow the practitioner to assess probabilities and impacts in a clinical manner. Properly executed, a risk assessment must treat severity and probability as independent variables. Although, the average person may see probability and severity as causally linked, the probability of the event is in no way related to the severity of the consequence. Severity does not cause probability, nor does probability cause severity. Probability is a function of frequency. Severity is a function of the physical nature and physics of the infrastructure and climatic event. Risk assesses the combined

implications of the two. This perspective allows the practitioner to rank the likelihood of events and the severity of events separately in order to rigorously evaluate the implications.

These concepts are technically complex and outside of the experience of the average person. Therefore it is the practitioner's duty to be vigilant in the execution of the protocol. They must ensure that these myths and misconceptions do not creep into the mindset of the practitioner team or workshop participants and compromise the veracity of the assessment results.

6 The Vulnerability Assessment Workshop

In Step 3 of the protocol, there is a requirement that the practitioner execute a workshop with the practitioner team and representatives from the infrastructure ownership and operations teams. This is the way to draw on the combined experience of the practitioner and people who have direct contact with the infrastructure. This method allows the team to apply professional judgment in a transparent and consistent manner. As stated above, this can be done in a technically rigorous way and yield results that can withstand professional scrutiny.

Where data exists, the practitioner is directly to use it. However, if the data is missing or suspect in any manner, the practitioner is directed to rely on the professional judgment of the practitioner team and workshop participants. Thus, the workshop represents the most important phase of the evaluation.

At the workshop the practitioner reviews the results of their prescreening assessment and invites participants to assess the probabilities and severities of the interactions identified by the practitioner. Although the protocol allows the practitioner to conduct the risk assessment through a series of one-on-one meetings, where necessary; experience to date demonstrates that a properly executed workshop yields the most robust risk analysis. It is therefore strongly recommend that the practitioner use a workshop unless there are significant, compelling and material, reasons to the contrary.

Given the importance of the workshop, it is critical that the right mix of knowledge, experience and professional skills be present. If the practitioner team has been structured properly, the professional skills and experience should be available to the workshop. However, the practitioner team may be missing hands-on experience with this particular infrastructure and local knowledge regarding climatic events and how the infrastructure and operations team responded to those events. Participants at the workshop can fill these gaps. It must be stressed that it is not sufficient to include only management and engineering staff from the infrastructure owner. Operations staff must also participate. It is not uncommon for operations staff and management/engineering staff to have a distinctly different perspective of climate-infrastructure interactions. Events that the management team view to be very significant may already have been encountered and addressed by the operations team.

For example, the management team may view that a severe snow event could prevent operations staff from executing their duties, while the operations staff have already experienced snow events of equal or greater severity and developed methods to address the problems they encountered. As often as not, these procedures are not formally documented and can only be described by the affected staff.

Although these perspectives may seem trivial on the surface, they are very significant indicators of how the staff will respond during severe climatic events that affect their operations responsibilities. This should emerge during the workshop discussions and forms a substantive input to the local knowledge data used by the practitioner to establish the risk profile.

Generally, participants at the workshop should include:

- The practitioner team;
- Representatives from the infrastructure management team;
- Representatives from the infrastructure engineering team;
- Representatives from the infrastructure operations team;
- Local expertise/knowledge regarding severe climatic events in the region and climatic events that may have affected the infrastructure;
- Representatives from the organization providing climate information;
- Representatives from any advisory groups or technical experts who may be supporting the vulnerability assessment; and
- Others deemed necessary by the infrastructure owner or practitioner team.

The workshop should follow a consistent agenda. Given the number of laypeople who may be involved, it is important to provided sufficient background on the exercise to all participants and establish the expected outcomes from the meeting. Generally, the workshop agenda should include:

- A brief presentation on climatic change and the implications for the region;
- A brief presentation on risk and risk assessment;
- A brief presentation on the work completed by the practitioner to date;
    - As a minimum, identifying the key interactions to be considered by workshop participants;
- Introduction of the spreadsheet or matrix developed by the practitioner in compliance with Step 3 of the protocol;
    - Explanation of the infrastructure components and climate events that the practitioner deems to be relevant;
    - Polling of the workshop to determine if potentially relevant infrastructure components or climate events have been missed;
        - At this stage of the process the probability and severity values will not have been entered into the matrix or spreadsheet;

- A tabletop exercise, drawing on the expertise of workshop participants, establishing probability and severity for each relevant interaction identified by the practitioner. This could be done by:
    - o Assigning groups to input data to hard copies of the matrix distributed to the workshop;
    - o Assigning groups to input data to laptops distributed throughout the workshop;
    - o As a single facilitated discussion filling in a master spreadsheet projected to the entire workshop; or
    - o Other methods as deemed appropriate.
- If appropriate, a site visit or tour of the infrastructure or of specific components of the infrastructure; and
- A summary of findings arising from the workshop.

Because of the length of the agenda, and the need for rigorous discussion, the practitioner should plan the workshop for one complete eight-hour day.

Given the amount of professional, billable, hours that will be consumed at the workshop, it is critical that the practitioner:

- Carefully plan the event in consultation with the infrastructure management and operations teams;
- Schedule it to maximize productive outcomes;
    - o Not before screening analysis is complete or before all necessary and relevant data has been accumulated; and
- Provide as much validated data and background information as possible.

7 Economic Considerations

Economic considerations permeate climate change infrastructure vulnerability assessment.

At the project level, the Project Partner must establish a scope for the project and work that scope within budgetary limitations. This may drive decisions regarding the use of regional climate modeling, which can be expensive, and the overall depth and reach of the assessment. Thus, economics may dictate a smaller, more focused, assessment. Under such constraints, it is the practitioner’s responsibility to work with the infrastructure owner to establish a scope of work that both addresses the owner’s immediate issues while maximizing the opportunity to extrapolate assessment results to other areas of interest to the infrastructure owner. That is, the practitioner must work with the owner to maximize the “bang for the buck”.

During the execution of the assessment, practitioners will often identify data gaps. When this occurs, the practitioner and Project Partner must assess the available mechanisms for obtaining or improving the data. This can also be an expensive exercise and must be evaluated based on the economic return associated with the task. For example, the data may be necessary to fully understand a risk associated with one sub-component of the infrastructure. If this sub-component is deemed to be critical with a significant economic penalty associated with its loss, the team may decide that the costs are justifiable. That is, the cost of the potential risk significantly outweighs the cost of filling the data gap. On the other hand, the data may be desired to characterize a risk that, in the grand scheme of things, is relatively minor. In this case, the team may decide to forego the expense of additional data acquisition. That is, the cost of the potential risk is much less than the cost of filling the data gap. These examples establish economic boundary conditions. During the actual execution of an assessment, significant professional judgment and consultation with the infrastructure owner may be required.

It should be noted that acquiring 100% of the data necessary to support a vulnerability assessment is normally outside of the economic reach of the assessment. Missing data is common and filling the gap can be very expensive. The protocol directs practitioners to use professional judgment to address these issues. One key element of this judgment is the economic implication of the methodologies the practitioner recommends to address the gap.

Finally, the practitioner may identify recommendations to address vulnerabilities identified by the assessment. Once again, the practitioner should take economic factors into consideration. For example, one potential solution to an identified vulnerability could be replacement of the infrastructure, with major capital expenditure. Since the assessment does not normally evaluate the engineering alternatives to address vulnerabilities at any depth, the practitioner should evaluate the implications of such a recommendation, in consultation with the owner, to assess the economic feasibility. Practitioners must not shy away from reporting identified vulnerabilities, but should take to care state their recommendations within the context of reasonable, economic constraints. In the example above, although full replacement may be ideal other, more cost effective, approaches may be available and should be considered. Ultimately, these considerations will play a role in the final acceptance of the assessment and its recommendations.

Appendix B

Site Selection Analysis

Climate Change Vulnerability Assessment- Site Selection Criteria

Introduction to these Spreadsheets

In order to evaluate and compare potential sites that could be used in an assessment of roadway and associated infrastructure's vulnerability due to climate change, a list of site selection criteria were developed. Each criteria has been given a weighting which indicates its relative importance in the site selection process.

For the purposes of the site evaluation, potential sites should be selected such that they include a section of roadway covering approximately 30 km to 40 km.

For each potential site(s), enter a rating between 0 (poor) and 5 (excellent) for each criteria on the "Site Rating" spreadsheet. This rating indicates the degree to which the site is a good candidate based on that specific criteria. The "Rating Guidelines" sheet provides a framework for how each rating should be selected.

Once a site has been rated on the "Site Rating" spreadsheet, a score for the site is automatically calculated on the "Site Scores" spreadsheet based on the criteria weighting and the site ratings.

Climate Change Vulnerability Assessment - Rating Guidelines for Site Selection Criteria

Site Selection Criteria		Rating Guidelines					
		0	1	2	3	4	5
Infrastructure	Infrastructure Age	Recent major improvements to roadway and infrastructure (<5 years)	Most of the roadway and infrastructure recently reconstructed (<10 years)	Most of the roadway and infrastructure is of moderate age (<20 years)	Mix of old (>50 years) and newer (<20 years) roadway and infrastructure	Most of the roadway and infrastructure is > 50 years old	No significant improvements to highway alignment or major infrastructure in >50 years
	Variety of Infrastructure	Little infrastructure beyond road structure					Wide variety of infrastructure along the route
Data Availability	Current Weather Data Available (weather stations)	No weather stations in or near (within 50 km) study area	At least 1 weather station within 200 km of study area	1 weather station within 100 km of study area	Multiple weather stations within 100 km of study area	2 weather stations within 50 km of study area	1 weather station at study area, additional weather station within 50 km
	Historic Weather Data Available (temperature, precipitation)	No historic weather data available	Historic data available for less than 50 years	Historic data available for 50 years, but station >100 km away	Historic data available for 50 years, but station >50 km away	Historic data available for 50 years and station within 50 km of study area	Historic data available for over 75 years and station within 50 km of study area
	Availability of Infrastructure Data	No information available	Limited information available - locations known for major infrastructure only (i.e. Bridges, large retaining walls)	Limited information available - locations and some details known for all major structures and some minor (i.e. Barrier, culverts)	Basic location and properties/ infrastructure types known - some drawings available for major infrastructure	Detailed information (drawings, locations, materials) available for most infrastructure	Detailed information available for all major infrastructure and most minor infrastructure
Environment	Occurrence of Extreme Environmental Events (such as flash flooding, prolonged flooding, ice jams, debris flows, landslides, avalanches, unusually high snow accumulation, etc.)	Area is not prone to extreme environmental events	One or two extreme environmental events have occurred within the past 50 years	Area is prone to one type of extreme environmental event that occurs infrequently	Extreme environmental events occur frequently, but only one type (i.e. avalanches occur most winters)	Various types of extreme environmental events have occurred, but relatively infrequently	Various types of extreme environmental events occur frequently
	Geotechnical Indicators (i.e. presence of collapsible silts, permafrost, oversteepened cuts/ fills, etc.)	No geotechnical indicators present in the area	One geotechnical indicator present in the area	Two or more geotechnical indicators present			Several geotechnical indicators present along the highway section
	Variety of Terrain	Flat terrain with few watercourses near highway, no watercourses intersecting highway	Flat terrain with few watercourses intersecting highway		Rolling or mountainous terrain with numerous water courses intersecting highway		Wide variety of terrain with numerous water courses intersecting highway
	Expected Climatic Change - Temperature	Climate change models predict no change for region (by 2050)	Climate change models predict minor temperature changes (±1°C)		Climate change models predict moderate temperature changes (±3°C)		Climate change models predict large temperature changes (more than ±5℃)
	Expected Climatic Change - Precipitation	Climate change models predict no change for region (by 2050)					Climate change models predict large precipitation changes
	Climatic Regions	N/A	Route covers 1 climatic region	N/A	Route covers 2 or more climatic regions	N/A	N/A
Other Criteria	Traffic Volumes	<300 AADT	301 to 1,000 AADT	1,001 to 5,000 AADT	5,001 to 10,000 AADT	10,001 to 20,000 AADT	> 20,000 AADT
	Strategic Importance of Route	Minor road, alternate routes available	Minor road, no viable alternate routes	Secondary route, alternate routes available	Secondary route, no viable alternate routes	Major economic corridor, alternate routes available	Major economic corridor, no viable alternate routes

Climate Change Vulnerability Assessment - Site Rating

Site Selection Criteria		Criteria Weighting 1 (less important) to 5 (more important)	Site Rating for each Criteria 0 (poor) to 5 (excellent)							
			Hwy 3, Kootenay Pass (between Salmo and Creston)	Hwy 31, Meadow Creek to Trout Lake	Hwy 16, Burns Lake to Smithers	Hwy 29, Chetwynd to Charlie Lake	Hwy 14, Sooke to Port Renfrew	Hwy 5, Coquihalla (between Hope and Merritt)	Hwy 3, Paulson Pass (between Christina Lake and Jct with Hwy 3B)	Hwy 16, Terrace to Prince Rupert
Infrastructure	Infrastructure Age	4	2	5	3	4	5	3	3	3
	Variety of Infrastructure	3	4	3	4	3	3	5	3	4
Data Availability	Current Weather Data Available	4	4	2	3	3	1	5	4	3
	Historic Weather Data Available	4	3	2	3	2	3	3	2	3
	Availability of Infrastructure Data	2	2	1	2	2	1	4	2	2
Environment	Occurrence of Extreme Environmental Events	5	3	5	3	2	3	3	3	4
	Geotechnical Indicators	3	4	4	3	3	2	2	2	5
	Variety of Terrain	4	3	3	3	4	3	5	2	5
	Expected Climatic Change - Temperature	2	5	5	3	3	3	5	5	3
	Expected Climatic Change - Precipitation	5	2	2	3	2	3	2	2	3
	Climatic Regions	2	1	1	1	3	1	3	1	1
Other Criteria	Traffic Volumes	2	2	1	2	1	1	4	2	2
	Strategic Importance of Route	3	4	2	5	3	2	4	5	5

Climate Change Vulnerability Assessment - Potential Site Scores

Site Selection Criteria		Criteria Weighting 1 (less important) to 5 (more important)	Site Scores (Criteria Weighting x Site Rating)							
			Hwy 3, Kootenay Pass (between Salmo and Creston)	Hwy 31, Meadow Creek to Trout Lake	Hwy 16, Burns Lake to Smithers	Hwy 29, Chetwynd to Charlie Lake	Hwy 14, Sooke to Port Renfrew	Hwy 5, Coquihalla (between Hope and Merritt)	Hwy 3, Paulson Pass (between Christina Lake and Jct with Hwy 3B)	Hwy 16, Terrace to Prince Rupert
Infrastructure	Infrastructure Age	4	8	20	12	16	20	12	12	12
	Variety of Infrastructure	3	12	9	12	9	9	15	9	12
Data Availability	Current Weather Data Available	4	16	8	12	12	4	20	16	12
	Historic Weather Data Available	4	12	8	12	8	12	12	8	12
	Availability of Infrastructure Data	2	4	2	4	4	2	8	4	4
Environment	Occurrence of Extreme Environmental Events	5	15	25	15	10	15	15	15	20
	Geotechnical Indicators	3	12	12	9	9	6	6	6	15
	Variety of Terrain	4	12	12	12	16	12	20	8	20
	Expected Climatic Change - Temperature	2	10	10	6	6	6	10	10	6
	Expected Climatic Change - Precipitation	5	10	10	15	10	15	10	10	15
	Climatic Regions	2	2	2	2	6	2	6	2	2
Other Criteria	Traffic Volumes	2	4	2	4	2	2	8	4	4
	Strategic Importance of Route	3	12	6	15	9	6	12	15	15
Overall Site Score			**129**	**126**	**130**	**117**	**111**	**154**	**119**	**149**

Appendix C

Completed Protocol Worksheet 1 and Attachments

In this step the practitioner will define the global project parameters. This step will define:

- Which particular infrastructure is being assessed;
- Its location;
- Unique climatic, geographic considerations; and
- Uses of the infrastructure.

This is the first step of narrowing the focus to allow efficient data acquisition and assessment.

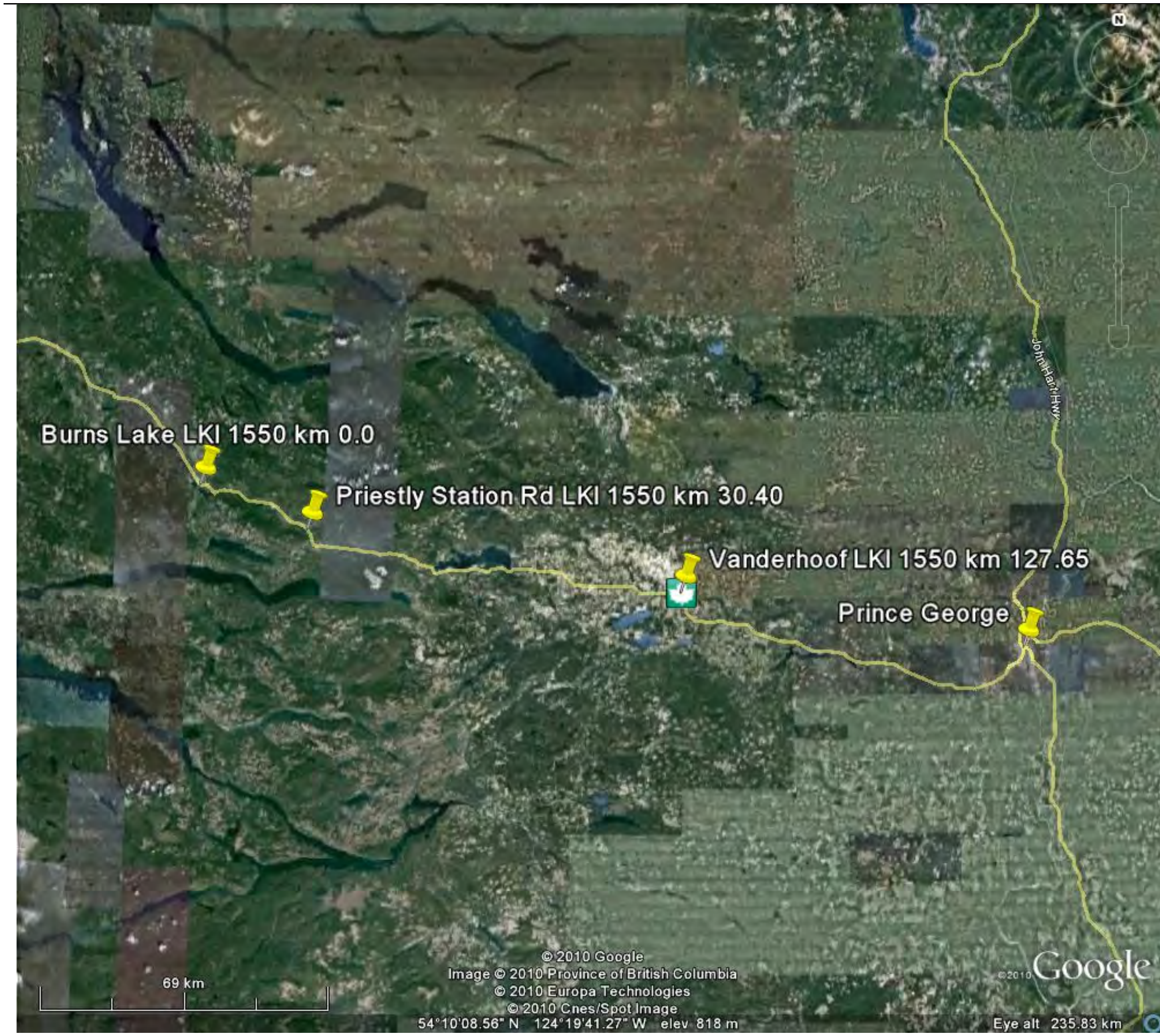
8.1.1 Identify Infrastructure which is to be evaluated for climate change vulnerability
Choose Infrastructure: BC Yellowhead Highway 16 between Vanderhoof and Priestly Hill (approximately Priestly Station Road)
General Description: From the eastern border with Alberta the Yellowhead Highway in British Columbia runs west through the Cariboo Mountains to Prince George, and through the Fraser Plateau, the Bulkley River Valley and the Skeena River Valley, before reaching the west coast at Prince Rupert. In 1942 the number '16' was assigned to the British Columbia portion of this road. The Yellowhead Highway closely follows the path of the northern B.C. alignment of the Canadian National Railway and in 1947 the western end of the highway was moved from New Hazelton to the coastal city of Prince Rupert. In 1953, the highway was extended east from Prince George to the Yellowhead Pass. In the late 1960's/very early 1970's, Hwy 16 was completed east from Prince George to the Yellowhead Pass (Tete Jaune Cache) with a series of construction/paving projects. If there was a link prior to 1970, it would have been not much better than a bunch of connected logging roads. The original surfacing for Hwy 16 west of Prince George is not well documented. It appears from the incomplete histograms that the first serious upgrading of the 155 km-long stretch between Prince George and Fraser Lake was

carried out between 1953 and 1960 when 450 to 600 mm of pit run gravel was placed and then capped with a 75mm thick pulvi-mix (cold mix) pavement surface (the east 135 km) or a sealcoat surface (the west 20 km).

The pit run gravel was likely highly variable in quality and size, and it appears there is no identifiable processed (crushed) base course layer beneath the pavement. From 1960 to 1995, a number of pavement patches, pavement overlays (including asphalt base course mixes, recycled asphalt pavements, and conventional pavements), chip seals, sealcoats, and crack seals have been carried out. Pavement thicknesses range from 200mm to 450mm, with an average of about 300mm.

Although the pavement structures are highly variable throughout this stretch of road with largely unknown parameters for the structure components, the road surface is very strong and there are no observable or measurable strength deficiencies – largely due to the thick pavement. Consequently, rehabilitation work carried out over the last 15 years has mostly included hot-in-place recycling and sealcoat treatments to improve/preserve the existing surface rather than increase its thickness.

Additional Background & Detailed Information Sources	
	Links and References
Google Map of Infrastructure	Inserted below.


Burns Lake LKI 1550 km 0.0
Priestly Station Rd LKI 1550 km 30.40
Vanderhoof LKI 1550 km 127.65
Prince George
John Hart Hwy
69 km
© 2010 Google
Image © 2010 Province of British Columbia
© 2010 Europa Technologies
© 2010 Cnes/Spot Image
54°10'08.56" N 124°19'41.27" W elev 818 m
Eye alt 235.83 km
Google

8.1.2 Identify Climate Factors of Interest

State general Climate factors to be considered

Although prior to the late '70s it was not unusual for the winter temperature in the Burns Lake to Prince George area to drop below -30 for a stretch of a couple of weeks or more each winter, this has not been the case since. In the last 18 years the temperature has not dropped to this extreme for more than a few days at a time, and perhaps only a couple of times per winter (some winters not at all).

The average summer (June, July, August) 1961-1990 temperatures in Prince George are a daytime high (maximum) of 21.1 °C and night-time low (minimum) of 7.5°C. The average winter (December, January, February) 1961-1990 temperatures are a maximum of -3.6°C and a minimum of -12.3°C. Annual mean (average of daytime high and night-time low) temperature for the 1961-1990 period was 3.7°C,

In the area immediately surrounding Prince George precipitation ranged from 450 mm to 1000 mm. In the western part of the region, which lies on the leeward side of the Coast Mountains, relatively low annual precipitation occurred (Figure 4.1-1b). Annual precipitation amounts in this area ranged from 450 mm to 750 mm. The areas east and north-east of Prince George, on the windward side of the Rocky Mountains, received between 750 mm and 2000 mm of precipitation annually.

Source:

> Climate Change in Prince George
> Summary of Past Trends and Future Projections
> Ian M. Picketts (University of Northern British Columbia)
> Arelia T. Werner, Trevor Q. Murdock (Pacific Climate Impacts Consortium)
> 31 August 2009

Drought can lead to exacerbated wildfire situations. These can lead to dramatically changed drainage conditions and significant debris flow issues. May also wish to consider the impact of lightening strikes that may exacerbate this concern.

Additional background & detailed information sources	
Castlegar B.C. PIEVC Case Study	Not available for general distribution. Will obtain copy when available before the end of the calendar year.
Collision Data	Collisions rates can be correlated with weather conditions. Information supplied by BC MoT as a PDF of an Excel spreadsheet.
Local Weather Station Data.	Map provided by BC Provincial Govt.
Study will also consider impact of increased precipitation on construction costs.	Precipitation data to be developed by PCIC.

8.1.3 Identify the Time Frame

The project will focus on two future climate projection timelines based on the years 2050 and 2080.

8.1.4 Identify the Geography

From the eastern border with Alberta the Yellowhead Highway in British Columbia runs west through the Cariboo Mountains to Prince George, and through the Fraser Plateau, the Bulkley River Valley and the Skeena River Valley, before reaching the west coast at Prince Rupert.

Notes:

8.1.5 Identify the Jurisdictional Considerations

- Rail
- Natural gas
- Transmission lines
- Bulkley Nechako Regional District
- First Nations
- Ministry Forestry
  - wild fire/lightening probability - contact Lyle Gawalko (Jim)
  - road strength
- Agriculture studies
- Ministry Environment studies – contact Jenny Fraser? (Jim)
- Environmental Assessments
- Kenny Dam, Nechako River
- Kemano Dam
- BC Hydro

• Alcan – gov't agreement with them regarding meteorological data • DFO	

8.1.6 Site Visit
Summary of Findings from Interviews
The project team concluded that a dedicated site visit was not necessary for this project since the team comprised personnel who work on this stretch of highway routinely.
Key Observations
N/A
Areas for Follow-up in Subsequent Steps
N/A

8.1.7 Assess Data Sufficiency

State Assumptions proposed for the assessment, if any	Rationale
Climate data available per PCIC, BC MoT	Pacific Institute for Climate Solutions with Pacific Climate Impacts Consortium has confirmed they have access to BC Climate information and will seek local knowledge to include MoT

	Meteorological Data Collection Stations on site
Where insufficient information currently available Identify process to develop data	**Process**
N/A	

Where data cannot be developed, identify the data gap as a finding in Step 5 of the Protocol – Recommendations.
List Data Gap as findings to be sent to STEP 5 (Worksheet 5: Section 8.5.2)
No significant data gaps identified through Step 1 of the Protocol

Prepared by:	Joel R. Nodelman, P.Eng. (On behalf of BC MoT)
Date:	November 24, 2010

Appendix D

Completed Protocol Worksheet 2

In this step the practitioner will provide further definition regarding the infrastructure and the particular climate effects that are being considered in the evaluation. The practitioner will undertake a data acquisition exercise and identify where, in their professional judgment, whether the data is insufficient due to:

- Poor quality;
- High levels of uncertainty; or
- Lack of data altogether.

This step further focuses the evaluation and starts to establish activities to in-fill poor quality or missing data.

8.2.1 State Infrastructure components that are to be evaluated for climate change vulnerability.

i. Only select those infrastructure components that, in the practitioner's professional judgment, are relevant to this assessment.
ii. Where available, review operations incident reports, daily logs and reports to assist in the identification of infrastructure elements with a history that could result in vulnerability and are relevant to this process.
iii. Interview infrastructure owners and operators to identify historical events that may not be documented or retrievable from databases and evaluate if these events are relevant to this assessment.

List Major Components	Information from Logs & Reports	References and Assumptions
Above Ground		
Asphalt		
Seal Coat		Seal coat reacts differently than asphalt to high temperature.
Pavement Marking		Differentiate between paint and thermal plastic and other driver guidance appliances. Also long line markings. Replenished on different schedules.
Shoulders (Including Gravel)		
Barriers		Concrete shoulders, bridges and flumes. May restrict

		drainage and snow plowing.
Curb		Asphalt curbing and concrete curbing. Asphalt curbing has shorter lifespan. Concrete on islands and intersections.
Luminaires		Vanderhoof for sure, new luminaires this year.
Poles		All sorts of poles.
Signage - Overhead Guide Signs		Some in urban areas.
Overhead Changeable Message Signs		Some "open" and "close" at weigh scales.
Ditches		
Embankments/Cuts		Soil embankment and cuts and rock embankment and cuts.
Hillsides		Includes all slope instability features. Raveling back slopes.
Protection Works		Rip wrap, or rock blankets. Matting and hydro seed. Not a whole lot of any one type. Erosion and sediment control design for construction projects.
Engineered Stabilization Works		
Structures that Cross Streams	District, Region, HQ files	Adequacy of engineering design for higher peak flows or other changing climate parameters. Fish passage design criteria (if a fish stream).
Structures that Cross other transportation systems		Cross railway.
District, Region, HQ files	Adequacy of engineering design for higher peak flows or other changing climate parameters. Fish passage design criteria (if a fish stream).	District, Region, HQ files
Retaining Walls		Yes and other retaining walls, bridges have abutments etc. May need to break out in late steps of the Protocol.

Fiber-Optic Cables – telephone, television		
Environmental Features		
Wild life passing structures		Bridge crossings may serve this purpose. Bridges and culverts may need to accommodate the passage of fish. Bridge structures opening design can enable terrestrial wildlife passage. Climate change issues may lead to a need to modify stream bank/end-fill armoring could conceivably affect passage under existing structures.
Below Ground		
Road Sub-Base		Road base. Road sub-base. Sub-grade.
Detail Drainage (what are the drainage sub-components		Mostly at bridges and retaining walls. Some at Priestley Hill, mostly surface details Include only if they affect geo-technical issues
Drainage Appliances		Storm drainage appliances. May not be actual storm sewers out there.
Sub-Drains		
Catch Basins		Storm drainage appliances. May be some catch basins.
Grates		
Culverts < 3m		• Includes trash racks and headwalls. • Open footing vs. closed footing. • Fish passage design criteria (*Fisheries Act* and *Water Act*) can drive structure sizing and potentially a need for a different structure type (i.e. larger opening and/or embedment or bottomless). • Changing flow characteristics can affect

		functionality of fish-passage culvert retrofit works. • *Navigable Waters Protection Act* design criteria.
Culverts ≥ 3m		• Includes trash racks and headwalls. • Open footing vs. closed footing. • Fish passage design criteria can drive structure sizing and potentially a need for a different structure type (i.e. larger opening and/or embedment or bottomless). • Changing flow characteristics can affect functionality of fish-passage culvert retrofit works. • *Navigable Waters Protection Act* design criteria.
Asphalt Spillway and Associated Piping/Culvert		Usually have small diameter culverts associated. Treat with culverts. Buffers in pipe, asphalt swale to prevent corrosion.
Gas or other Distribution Lines.		
Power lines • Along and across highway		
Web Cams		Weather condition monitoring.
Distribution and Wastewater Systems		Wells. Water lines. Etc.
Third Party Utilities		High-pressure gas. High-pressure oil. Fiber optic cable – not as relevant.-above ground.
Miscellaneous		
Administration/Personnel		N/A
Winter Maintenance		Ongoing. Check difference in resource usage, i.e. salt or sand as proxy.

Ancillary Buildings and Utilities and Yards.		Outhouses and rest areas. Telus and Pacific Northern Gas have buildings on right of way. Weigh Scale site/ shack Maintenance yards including material storage.
Habitat Features		
Maintenance (Markings, Crack Sealing)		

8.2.2 State Climate Baseline

State general Climate Parameters for use in STEP 3 of Assessment **(Reference Appendix A– Climate Event and Change Factors)** **(Additional Reference – Adapting to Climate Change, Canada's First National Engineering Vulnerability Assessment of Public Infrastructure; Appendix D - Canada-Wide Sampling Study)**	**Climate information Source**

Temperature
• Freeze-thaw
  o Want to have idea of frequency of freeze/thaw
  o Plus how rapidly the cycle occurs (can use historical data, or maintenance records)
• Max-Min
	• Can be provided by modifying the Climdex indices.
	• Maintenance schedule dependent on threshold, which triggers maintenance actions (recorded).

Freezing rain, or wet snow, or Rain + Snow	• Possibly from daily or 3-hourly T and P.
Precipitation	• Can be provided by modifying the Climdex indices.

• As snow • As rain • Hail. Visibility and precipitation. Highway safety and can block drainage. If Team can't get data this may lead to a finding.	
Dry days and maximum temperature collected for 7-day periods	• Using a running window?
River flows and volumes • Water surface elevation • High water marks • Ice jams.	• Can be provided by modifying the Climdex indices.
Ice: • Freezing rain • Ice accretion • Ice storms	As analogue use rainfall when temperature < 0^{o} C.
Visibility • Heavy Fog and • Hail • Smoke from forest fire	
Solar Radiation	• Can be provided by modifying the Climdex indices. • Shortwave radiation • Aging of infrastructure components
Change in Climatic Regions within study area	Some minor changes across the area. Not significant.
Lightning	
Lake Effects	Fraser Lake usually freezes

List Historical Extreme Climate Events				
Event	**Frequency**	**Normal Duration**	**Magnitude**	**State Justification for Infilling Missing Data**
Days with Max Temp > 35 °C				Can be provided by modifying the Climdex indices.
Days with Min Temp < 30 °C				Can be provided by modifying the Climdex indices.
Daily Temp variation > 25 °C				Can be provided by modifying the Climdex indices.
≥ 85 days with Max Temp > 0 °C and Min Temp < 0 °C				
≥ 47 days with Min Temp < 0 °C				Can be provided by modifying the Climdex indices.
≥ 5 consecutive days with > 25 mm rain				Can be provided by modifying the Climdex indices. To be confirmed with PCIC.
≥ 23 consecutive days with > 10 mm rain				Can be provided by modifying the Climdex indices. To be confirmed with PCIC.
≥ 112 consecutive days with > 0.2 mm rain				Can be provided by modifying the Climdex indices. To be confirmed with PCIC.
≥ 10 consecutive days with rain or snow				Cannot be done with models.
≥ 3 days with rain that falls as liquid and freezes on contact				Cannot be done with models.
≥ 5 consecutive days with snow				Cannot be done with models.

> 10 cm				
≥ 8 days with blowing snow				May be able to develop this with models.
≥ 5 days with snow depth > 20 cm				Cannot be done with models.
Days with precipitation falling as ice particles				Cannot be done with models.
≥ 8 days with Max winds ≥ 63 km/hr				Cannot be done with models.
≥ 10 consecutive days with precipitation < 0.2 mm				Cannot be done with models.
Average maximum temp over seven days				
Rain on snow including temperature and wind speed				The rain that is the issue
≥ 15 hours per year with visibility < 1,000 m				
				Needs to include list of factors used to predict issues. Commonly used criteria. Covers shallow landslides and debris torrents.

8.2.3 State Climate Change Assumptions	
Relevance & Applicability of Observed Global or Regional Climate Change Trends with respect to the Infrastructure	**Document How These Trends Influence the Infrastructure**
If climate modeling unavailable may apply to specific climate parameters.	TBD based on availability of modeling data.
% Increase or Decrease to Climate Change Baseline Based on TRENDS	**Justification/Substantiation**

If climate modeling unavailable may apply to specific climate parameters.	TBD based on availability of modeling data.
% Increase or Decrease to Climate Change Baseline Based on SENSITIVITY ANALYSIS	**Justification/Substantiation**
If climate modeling unavailable may apply to specific climate parameters.	TBD based on availability of modeling data.
% Increase or Decrease to Climate Change Baseline Based on SURROGATE INFORMATION	**Justification/Substantiation**
If climate modeling unavailable may apply to specific climate parameters.	TBD based on availability of modeling data.
% Increase or Decrease to Climate Change Baseline Based on USER DEFINED (ARBITRARY) CLIMATE CHAGE ASSUMPTIONS	**Justification/Substantiation**
If climate modeling unavailable may apply to specific climate parameters.	TBD based on availability of modeling data.
% Increase or Decrease to Climate Change Baseline Based on REGIONAL CLIMATE MODELS	**Justification/Substantiation**
Using RCMs from NARCCAP, simulating actual weather (1980-2003) and present (1968-2000) and future (2038-2069) climate simulated from greenhouse gases (emission scenario A2)	Standard approach used successfully in the Coquihalla Vulnerability Assessment

8.2.4 State Time Frame	
Infrastructure Safe Operation Time Period	**Time (Years)**
	50 to 70 Years
Design Life of Infrastructure Components	

Infrastructure Component	Time (Years)
Above Ground	
Asphalt - Hot in Place	10 Years
Asphalt - Seal Coat	7 Years
Pavement Marking	1Year
Shoulders (Including Gravel)	Annual grading; more veg, more weed removal; sod removal, not every year. Shoulder rehab every 4 years etc. (more intense rain could increase need to maintain)
Barriers	30
Curb - Concrete	4-6 Years Winter plowing can cause wear on elements that stick out. 20 years Parts that do not stick out – islands etc. Heavy snow, may not see structure
Curb - Asphalt	4-6 Years May be reduced by winter plowing.
Luminaires	Normally replaced as they break ~ 10 per year Mostly break from vehicle collisions (long load trucks turning etc.)
Poles	25 to 30 years
Signs - Sheeting - Wood or metal base	Sheeting = 12 Years Rest of sign elements = 25 to 30 Years Throw from snow plow causes damage. CC can affect: may have to review sign design parameters. Snow drifts: from surrounding farms, snow fence
Signage - Side Mounted - Over 3.2 m^2	No need
Signage - Overhead Guide Signs	Not need
Overhead Changeable Message Signs – Weigh Scale	20+ Years Power outage can impact operability. Close to Vanderhoof, can restore fairly quickly, otherwise may take longer to restore power.
Ditches	3-5 Years based on maintenance, weed removal. Must ensure that they

	are deep enough. Increases in rain and snow may impact functionality. Intense rain can cause erosion esp. after lots of heavy rain. There are capacity/design issues today. Currently use 1 in 10 return period (Mike Feduk)
Embankments/Cuts	Life of Project – Will not change.
Hillsides	Life of Project
Engineered Stabilization Works	75+ Years Same as bridges.
Structures that Cross Streams - Bridges	75+ Years Newer designs.
Structures that Cross Roads - Bridges	75+ Years Newer designs.
Railways	Cross Roads
River Training Works - Rip Rap	Life of Project. 1 in 200 year event for rip rap.
Retaining Walls - RICO Walls	75 years
Asphalt Spillway and Associated Piping – Above Ground Elements	10-15 Years
Below Ground	
Pavement Structure	20-25 Years Life of Infrastructure
Catch Basins	Life of Project based on a 10 to 25 Return Period.
Roadway Drainage Appliances	Life of Project
Sub-Drains	Life of Project
Distribution Systems	Specified in permit. Life of Infrastructure.
Third party utilities	Specified in permit. Life of Infrastructure.
Culverts < 3m	15 Years under major highway. Otherwise, 50 to 75 Years.

	Based on 1 in 100 year return period.
Culverts ≥ 3m	20 Years under major highway: Otherwise, 50 to 75 Year design life based on 1 in 100 year return period. Corrugated steel pipes were not galvanized as well in the past. Could reduce life to 25 to 30 Years. Acidic soils, corrosion, heavy loads also impact serviceability. Erosion can grind the bottom out. On average 40 years.
Asphalt Spillway and Associated Piping/Culvert - Below Ground Elements.	10-15 Years
Miscellaneous	
Winter Maintenance	Ongoing
Habitat Features	25 Years – dependent on flow. Baffles for fish etc. can decrease flow etc.
Routine Maintenance	Ongoing Standards need to be reconsidered. Need overarching plan regarding 10 Year Maintenance Contracting
Useful Life Remaining	**Time (Years)**
	Ongoing. Depend on component.
Other Relevant Comments	
As noted above.	

8.2.5 Geography	
Major Components of local geography	**Reference**
From the eastern border with Alberta the Yellowhead Highway in British Columbia runs west through the Caribou Mountains to Prince George, and through the Fraser Plateau, the Bukley River Valley and the Skeena River Valley, before reaching the west coast.	

Fraser Lakes	
Nechako River - Dam controlled. Dams may not last through the life of the study.	
Kenny Dam – May need to consider dam breach scenarios including wash outs and open gates.	
8.2.6 Specific Jurisdictional Considerations	
Jurisdiction With Direct Control or Influence on Infrastructure	**Reference**
BC MoT	
Fisheries and Oceans Canada (DFO)	*Fisheries Act* requirements will influence the design of replacement structures on fish streams.
Industry Canada	Regulates Radio and Electronics as well as Explosive use
Pipelines (NEB) Natural gas etc.	May have some influence on maintenance and refurbishment
Rail	
Transmission Lines	
First Nations	
Bulkley-Nechako Regional District	
Ministry of Forestry	
Ministry of Agriculture	
Ministry of Environment	*Water Act* requirements will influence the design of replacement structures.
Transport Canada	*Navigable Waters Protection Act* requirements will influence the design of replacement structures.
Alcan	
Sections of laws and bylaws that establish legal structure for the infrastructure	**Reference**
BC Wildlife Act	
BC Water Act	
Transportation Act	No bylaws
Motor Vehicle Act and Regulations	

Agricultural Land Reserve Act	
Agricultural Land Commission Act	
Land Act	
BC Railway Act	
Federal Railways Act	
Federal *Navigable Waters Protection Act*	
Build BC Act	
Builders Lien Act	
Coastal Ferries Act	
Commercial Transport Act	
Dike Maintenance Act	
Diking Authority Act	
Drinking Water ACT	
Forests Act	
Sections of regulations that establish legal structure for the infrastructure	**Reference**
As defined in Worksheet 1	n/a
Relevant Standards for the design, operation and maintenance of the infrastructure	**Reference**
BC Supplements to the Design Manual	
BC Design Manual	
Best Practices Documents	
Fish-stream Crossing Guidebook	http://www.for.gov.bc.ca/tasb/legsregs/fpc/FPCGUIDE/FishStreamCrossing/FSCGdBk.pdf
Infrastructure owner/operator administrative processes and policies as they apply to the infrastructure	**Reference**
Variances from chief engineers office	

8.2.7 Other Change Effects	
Changes in use pattern that increase/decrease the capacity of the infrastructure	**Reference**
More truck traffic. More private vehicle traffic.	
River and watershed metamorphosis.	
Fire history and things that affect fire history (Mountain Pine Beetle)	
Deforestation	
Operation and maintenance practices that increase/decrease capacity of infrastructure	**Reference**
Rehab and Maintenance	Rehab depends on budget. Could take longer.
Changes in management policy that affect the load pattern on the infrastructure	**Reference**
N/A	
Changes in Laws, Regulations and Standards that affect the load pattern on the infrastructure	**Reference**
N/A	
8.2.8 Assess Data Sufficiency	
Comment on using relatively short term measurements to make long term predictions	**Limitations**
The team has many years of experience with day-to-day operation of the infrastructure. They were confident that this experience augmented with solid design and climatic data	

mitigated concerns regarding the use of short-term measurements to make long-term projections.	

Data Evaluation	Comment	Effect on Assessment
Data Gaps	As describe below.	Unable to assess high wind/ downburst or visibility concerns.
Data Quality	Statistical data has uncertainty associated with it.	Minimal. Compensated by team experience.
Data Accuracy	Data uncertainty	Minimal. Compensated by team experience.
Applicability of Trends	Use of experience based data and synoptic analysis relies significantly on observed trends.	PCIC projections and hands-on experience generally consistent with synoptic analysis, where they overlap.
Reliability of Selected Climate Models	All RCMs have inherent biases and uncertainties.	Minimal. Compensated by using cohort of model results and calibrating model outputs with the observed, baseline climate.
Other Factors	N/A	N/A

8.2.8 (c)

Establish Priority in Referenced Documents

Reference Document	Reference Priority (highest reliance first)
Variances from chief engineers office	**1**
BC Supplements to the Design Manual	**2**
BC Design Manual	**3**
Best Practices Documents	**4**

8.2.8 (d)	
Data Sufficiency	
Identify process to develop data, where insufficient	
Data Needed	**Process**
Based on the project schedule and limitations in climate modeling, PCIC was unable to provide model-based projections for the following climate parameters:	
Rain on Snow	Sensitivity Analysis
Freezing Rain	Sensitivity Analysis
Snow Accumulation	Sensitivity Analysis
Visibility	Sensitivity Analysis based on Collision Data
Where data cannot be developed, identify the data gap as a finding in Step 5 of the Protocol – Recommendations.	
List Data Gap as findings to be sent to STEP 5 (Worksheet 5: Section 8.5.2)	

Date:	**November 29, 2010**
Prepared by:	**Joel R. Nodelman on behalf of BCMoT Team**

Appendix E

Pacific Climate Impacts Consortium Summary Report

PACIFIC CLIMATE IMPACTS CONSORTIUM

Climate Change at the Yellowhead Highway

PCIC assessment for BCMoTI

February 21, 2011

G. Bürger, PCIC
J. Hiebert, PCIC
H. Eckstrand, PCIC

General introduction

One of the consequences of a warming climate is a corresponding shift in precipitation patterns. It is generally agreed that in a warmer world, dry areas tend to become drier and wet areas wetter *http://www.gfdl.noaa.gov/noaa-gfdl-climate-research-highlights-ar4*. Specifically, with atmospheric moisture converging in the tropics and at higher latitudes, these areas become wetter while the sub-tropics and mid-latitudes will likely experience drying. This drying and wetting pattern is a robust feature in all climate models, although the exact location of the transition zone varies. For a topographically rich zone such as British Columbia that zone is strongly modified by the local conditions of mountains and valleys and their orientation. Assessments of climate change and its impact for British Columbia are therefore particularly challenging. Results likely depend on the climate model in use, and generally need some form of adjustment and downscaling for obtaining reliable and useful results. However, going northward in British Columbia usually means going towards wetter conditions.

As detailed below, this tendency towards wetter conditions was also projected in the climate assessment for the Coquihalla (South) (*http://pacificclimate.org/project/climate-change-adaptation-engineering-applications-coquihalla-highway*) and the Yellowhead Highway (North). This second PIEVC climate assessment conducted by the Pacific Climate Impacts Consortium (PCIC) has drawn largely on experience gained from the first assessment, but has been streamlined and simplified to focus on the relevant quantities. We again rely on the regional climate model simulations of NARCCAP, this time evaluated for the Yellowhead area and with climate parameters that were defined by the local engineers. There are two significant enhancements compared to the Coquihalla study: a) The use of six instead of three climate models; b) A full statistical downscaling study is conducted that allows for the estimation of local extremes and their present and future statistics, so as to obtain direct estimates for the respective engineering design values; the analysis, moreover, covers the entire 21st and 22nd century.

We note that the findings of this study are in broad agreement with an earlier study conducted by PCIC for nearby the area of Prince George [Picketts et al., 2009] (see also *http://pacificclimate.org/content/climate-change-prince-george-summary-past-trends-and-future-projections*). While the focus of that study was more on the impact of natural fluctuations (such as the Pacific Decadal and the El Niño Southern Oscillation) and corresponding uncertainty of climate projections, the reported seasonal climate signals (increase in average temperature and precipitation) are in broad agreement with the projections reported here. This assessment of the Yellowhead highway supplements those earlier findings by analyzing the climatic impact on extremes, which are more relevant from an engineering viewpoint.

1. Data base

Our assessment of climate change for the Yellowhead Highway is based on statistics for present climate based on station observations, combined with information derived from regional climate models (RCMs) that are driven by global climate models (GCMs), both for present and future greenhouse gas concentrations.

a) Station observations

From the 19 Environment Canada stations near the highway, listed in Table 1, the present climate of the area was estimated. We used the three core variables

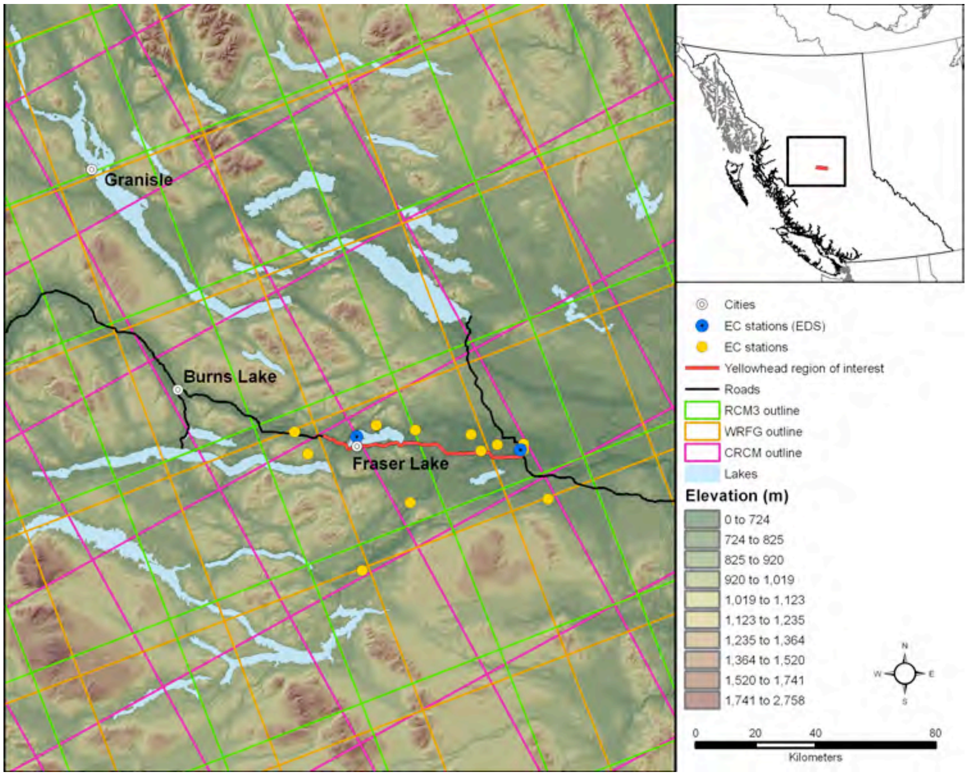


Figure 1. The Yellowhead Highway with nearby climate stations.

- daily minimum temperature, T_{min}
- daily maximum temperature, T_{max}
- daily precipitation, *P*.

In comparisons with RCMs, we formed daily averages across the stations.

b) GCM/RCM modeling

These are the six pairs of models that were used (GCM driving RCM denoted by GCM / RCM):

- CGCM3 / CRCM
- HadCM3 / HRM3
- GFDL / RCM3

- CGCM3 / RCM3
- CCSM / MM5I
- CCSM / WRFG

Details about the models can be found at *http://www.narccap.ucar.edu/data/model-info.html*. For brevity, the above model combinations will be referenced by the respective RCM.

Each RCM projection comes in its own grid with tiles of size 50km x 50km. For the analysis we selected for each RCM the tile that had the greatest overlap with the study area. The GCMs were driven by two different emission scenarios:

- **20C3M ("present"):** Greenhouse gasses increasing as observed through the 20th century.
- **A2 ("future"):** A very heterogeneous world. The underlying theme is that of strengthening regional cultural identities, with an emphasis on family values and local traditions, high population growth, and less concern for rapid economic development.

Climate averages are estimated as follows: for present climate the period 1971 to 2000 was chosen, for medium-term future (mid-century) the period 2041 to 2070 (short: 2050s), and for long-term future (late-century) 2085 to 2115 (short: 2100s). For the RCM based results only the 2050s were available.

For information on the details of these scenarios please consult *http://www.ipcc-data.org/ar4/gcm_data.html*

2. Method

a) Probability mapping

The main idea behind probability mapping is quite simple: Suppose a heavy rainfall event occurred, leading to a recording of 50mm/d precipitation at some local weather station. Unless it is a very localized event one will see rainfall in an entire area, with similar readings at nearby stations. Most likely, not all readings will show a value of 50mm/d, so the overall average precipitation that falls on that day in the area will be less. In other words: For most local extreme events there is a corresponding extreme event at a larger scale, whose size is typically reduced as it represents average conditions. The method of probability mapping captures this transition of local to larger scales, by identifying events (scales) that have equal probability [cf. Panofsky and Brier, 1958]. With this identification it is possible to derive a change in event probabilities directly from the larger (RCM) scales.

Specifically, suppose for a local variable, such as daily maximum temperature at some station, denoted by x, and a regional variable, X, say daily temperature at a corresponding RCM gridcell, we look at events

- $E_L(t, d)$: $x>t$ for d consecutive days (local)
- $E_R(T, d, \text{"present"})$: $X>T$ for d consecutive days (regional)
- $E_R(T, d, \text{"future"})$: $X>T$ for d consecutive days (regional)

Given some local threshold t, cf. Table 3, we determine the local probability $p_{\text{present}} = p(E_L(t, d))$. Using p_{present}, we find a regional threshold T_R, cf. Table 5, for the RCM so that $p(E_R(T_R, d, \text{"present"})) = p_{\text{present}}$. Using that threshold T_R we now determine the desired future probability of the event $p_{\text{future}} = p(E_R(T_R, d, \text{"future"}))$. The mapping scheme is displayed in Figure 1.

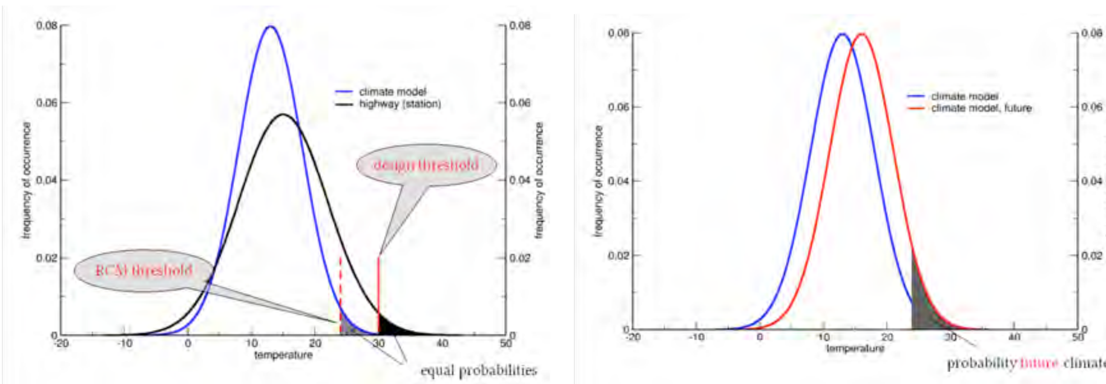


Figure 1. Probability mapping. Local and large event scales of equal probability are identified, and future probabilities are derived from the large (RCM) scales.

To assign a probability for a particular event (and define the probability mapping), that event should occur at least once in the observational record, which was not always the case for the original climate table. In a fruitful exchange between the Engineers and PCIC a compromise was found in each case and corresponding thresholds adjusted properly. The result is shown in Table 4.

b) Statistical Downscaling

Probability mapping is a parsimonious method that can be applied without much data processing and model calibration. Consequently, by providing mere probability estimates for predefined events it does not provide the detail that is often necessary to obtain reliable statistical estimates. For example, one cannot derive the typical scale of a 100-year rainfall event for the end of the 21st century.

A standard way of assessing the local impact of climate is by employing statistical (empirical) downscaling. Just like probability mapping, the goal of statistical downscaling is, as the name suggests, obtaining a quantitative link between the large-scale atmospheric circulation and local scale climate or weather events. For example, how is a summer heat wave with record temperatures and sustained drought possibly related to/caused by large-scale atmospheric flow patterns, such as a high-pressure blocking system over the North-Eastern Pacific? - Once such a relationship has been established on the basis of large and small scale observations, it can be applied to simulated atmospheric fields, such as those from climate models, to provide present and future downscaled climate data representative of the local scale.

For the Yellowhead assessment we have applied the expanded downscaling (EDS) method. EDS is born out of the idea to simulate local events that are as close to and consistent with the prevailing atmospheric circulation, but at the same time generate local covariability that is realistic enough to be used for studying the climatic impact on weather extremes, such as floods and droughts, and drive corresponding impact models. For details on EDS, see [Bürger, 1996; Bürger et al., 2009].

3. Results

Generally, an increase in temperature and precipitation values is projected. This is the common feature of the probability mappings and the statistical downscaling, and the impact on basically any particular climate event below can be traced back to this core tendency.

a) *Probability mapping*

The main results of the probability mapping are contained in the attached table "Probabilities"; we have summarized the main results here in Table 2. From this we conclude that rising temperatures has the strongest effect on cold extremes, as events of T_{min} < -35°C will become much rarer in a future climate (five per year to less than one per year). Likewise, but not so pronounced, there will be an increase of very hot days (T_{max} > 35°C, not shown). Except for one model system (HADCM3/HRM3) an increase in heavy precipitation events (*P > 35mm/d*) is projected; the actual projected probability is uncertain, nevertheless, due to the small sampling size (0.03 = one event in 30 years). Across all models ground freeze (T_{max} < -5°C) is projected to occur less frequent. A very important but hard to predict quantity is snow accumulation. There was only one model (CRCM) which reports snow accumulation, which limits our confidence in this quantity. This model, however, clearly projects a decrease in snowpack. This result is supported by the statistical downscaling.

b) *Statistical downscaling*

The results of the EDS-based statistical downscaling are daily time series of the three variables T_{min}, T_{max}, and *P*. From these, annual time series are derived using the 27 Climdex indices, as defined by the WMO [Easterling et al., 2003], see also (*http://www.ncdc.noaa.gov/oa/wmo/ccl*). Augmented by TN50p and TX50p to reflect median temperature values, all timeseries are provided in the attachment "Climdex time series". Figures 1 shows for the station of Fraser Lake (109C0LF) a selection of eight important indices, as downscaled from global climate scenarios that are driven by greenhouse gas concentrations based on three different socioeconomic storylines (scenarios). Besides the A2 scenario described above, these are:

- **20C ("present" and "future"):** the evolution of observed concentrations for the 20th century (as 20C3m above), followed by a commitment scenario with concentrations frozen to the state of year 2000
- **A1B ("future"):** A more integrated world (global ΔT = +1.4 to +6.4 °C)

While for the 20C scenario all quantities remain relatively stationary up to the end of the 21st century, the A1B and A2 scenarios result in a marked change, especially with respect to the temperature related quantities. According to Figure 1a, the number of frost days (FD) sharply declines from about 200 to only about 150 by the year 2100; likewise, the number of ice days (IC) is decreasing; on the opposite (temperature) side, the growing season length (GSL) increases from roughly 170 now to nearly 200 by the end of this century. Precipitation totals (PRCTOT) may increase from 500 mm to about 600 mm, roughly corresponding to the values reported by [Pickett et al., 2009]. Figure 1b shows Climdex values for extreme precipitation. It illustrates how the number of extreme events per year changes (from about 10 to 15 for R10 and from 2 to 3 for R20), as well as the amount coming from extreme events (from about 100 mm to 150 mm for R95p and from roughly 30 mm to 50 mm for R99p). Finally, Figure 2 illustrates the effect of a changed climate on the possible temperature extremes of the area of the Yellowhead. The portion of days where the maximum temperature is above the present-day median (TX50p) increases from 50% to almost 80% by the end of the century; likewise, for the 90% quantile this portion (TX90p) increases from 10% to 25%. In terms of actual temperatures, it is projected that the annual minimum of T_{max} (TXn) increases from -25°C to -20°C until 2100. For annual maxima of T_{max} (TXx) values which are presently safely below the 35°C mark will start to cross this line by mid century and even approach and exceed 40°C by the end.

c) Rain and snow

Rain and snow are not separately measured or simulated, but appear lumped together as precipitation. However, using a temperature threshold of near zero both quantities can approximately be recovered. Based on measured snow-depth data from the area, the error introduced from having below threshold rainfall and above-threshold snow data is limited, as shown in Figure 3. This was done for the daily observed and simulated (downscaled) values, and corresponding future estimates were thus obtained. Figure 4 shows the annual snow series for the stations of Fraser Lake and Vanderhoof; the derived rainfall characteristics are very similar to those of precipitation in general and are not shown. Figure 4a is for annual means, and it mainly shows a slightly negative trend towards the end of the simulation period at year 2200. This is probably the effect of a shorter winter season. Annual maxima, shown in Figure 4b, basically remain stationary, with some chances of a slight (but likely insignificant) decrease for Vanderhoof. These tendencies are in correspondence with the decreasing probabilities for snow accumulation of CGCM3/CRCM, as derived from the probability mappings above.

4. References

Bürger, G. (1996), Expanded downscaling for generating local weather scenarios, *Clim. Res*, *7*, 111–128.

Bürger, G., D. Reusser, and D. Kneis (2009), Early flood warnings from empirical (expanded) downscaling of the full ECMWF Ensemble Prediction System, *Water Resources Research*, *45*(10), W10443.

Easterling, D., L. Alexander, A. Mokssit, and V. Detemmerman (2003), CCI/CLIVAR workshop to develop priority climate indices, *Bulletin of the American Meteorological Society*, *84*(10), 1403-1407.

Panofsky, H. A., and G. W. Brier (1958), *Some applications of statistics to meteorology*, The Pennsylvania State University Pennsylvania.

Picketts, I. M., A. T. Werner and T. Q. Murdock, 2009: Climate change in Prince George: summary of past trends and future projections. Pacific Climate Impacts Consortium, University of Victoria, Victoria BC, 48 pp.

5. List of Tables

Table 1. *Environment Canada stations used as observations and for EDS (bold).*

Station Name	Station ID	Elevation	Latitude	Longitude
Fort Fraser	1092904	701	54.10	-124.55
Mapes	1094897	785	53.88	-123.88
Nechako River (AUT)	1085415	715	53.68	-124.83
Endako Mine	1092676	985	54.03	-125.10
Endako Savory	1092678	689	54.10	-125.17
Engen	1092685	706	54.03	-124.22
Fort Fraser 13S	1092905	701	53.88	-124.58
Vanderhoof	**1098490**	**638**	**54.05**	**-124.00**
Vanderhoof 2NE	1098492	677	54.03	-124.00
Vanderhoof	10984R0	674	54.05	-124.13
Vanderhoof	1098D90	638	54.03	-124.02
Vanderhoof Braeside Rd	1098DR0	683	54.08	-124.27
Fraser Lake North Shore	109C0L6	666	54.12	-124.75
Fraser Lake North Shore	**109C0LF**	**674**	**54.08**	**-124.85**

Table 2. *Main results of probability mapping. Observed probabilities (bold) refer to 1971 to 2000 averages, and simulated probabilities to 2041 to 2070. Probabilities are in events per year.*

	high temperature	low temperature	extreme rainfall	ground freeze	snow acc.
obs	**0.07**	**4.59**	**0.08**	**39.80**	**0.23**
CGCM3/CRCM	0.00	1.58	0.67	24.00	0.09
	0.00	1.64	0.67	24.40	0.09
CGCM3/RCM3	0.15	1.18	0.18	25.80	
	0.12	1.33	0.52	25.40	
GFDL/RCM3	1.55	0.85	0.12	27.50	
	1.70	0.85	0.18	27.10	
HADCM3/HRM3	1.67	0.21	0.06	25.90	
	1.88	0.00	0.03	25.90	
CCSM/MM5I	0.00	0.33	0.12	23.50	
	0.00	0.33	0.15	24.00	

CCSM/WRFG	0.03	0.52	0.18	26.70	
	0.15	0.49	0.33	26.70	

Table 3. Climdex indices

	ID	Indicator name	Definitions	units
1	CDD	Consecutive dry days	Maximum number of consecutive days with RR<1mm	Days
2	CSDI	Cold spell duration	Days with at least 6 consecutive days when $TN<Q_{10}$	Days
3	CWD	Consecutive wet days	Maximum number of consecutive days with RR>=1mm	Days
4	DTR	Diurnal T range	Monthly mean difference between TX and TN	ºC
5	FD0	Frost days	Annual count when TN(daily minimum)<0ºC	Days
6	GSL	Growing season Length	Days between first and last span of at least 6 warm enough days	Days
7	ID0	Ice days	Annual count when TX(daily maximum)<0ºC	Days
8	PRCPTOT	Annual total wet-day precipitation	Annual total PRCP in wet days (RR>=1mm)	mm
9	R10	Number of heavy precipitation days	Annual count of days when PRCP>=10mm	Days
10	R20	Number of very heavy precipitation days	Annual count of days when PRCP>=20mm	Days
11	R95p	Very wet days	Annual total PRCP when RR>95th percentile	mm
12	R99p	Extremely wet days	Annual total PRCP when RR>99th percentile	mm
13	Rnn	Number of days above nn mm	Days when PRCP>=nn mm, nn is user defined threshold	Days
14	RX1day	Max 1-day precipitation	Monthly maximum 1-day precipitation	mm
15	Rx5day	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
16	SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days (PRCP>=1.0mm)	mm
17	SU25	Summer days	Annual count when TX(daily maximum)>25ºC	Days
18	TN10p	Cool nights	Percentage of days when TN<10th percentile	Days
19	TN50p	Median Tmin	Percentage of days when TN>50th percentile	Days
20	TN90p	Warm nights	Percentage of days when TN>90th percentile	Days
21	TNn	Min Tmin	Monthly minimum value of daily minimum temp	ºC
22	TNx	Max Tmin	Monthly maximum value of daily minimum temp	ºC
23	TR20	Tropical nights	Annual count when TN(daily minimum)>20ºC	Days
24	TX10p	Cool days	Percentage of days when TX<10th percentile	Days
25	TX50p	Median Tmax	Percentage of days when TX>50th percentile	Days
26	TX90p	Warm days	Percentage of days when TX>90th percentile	Days
27	TXn	Min Tmax	Monthly minimum value of daily maximum temp	ºC
28	TXx	Max Tmax	Monthly maximum value of daily maximum temp	ºC
29	WSDI	Warm spell duration	Days with at least 6 consecutive days when $TX>Q_{90}$	Days

List of Figures

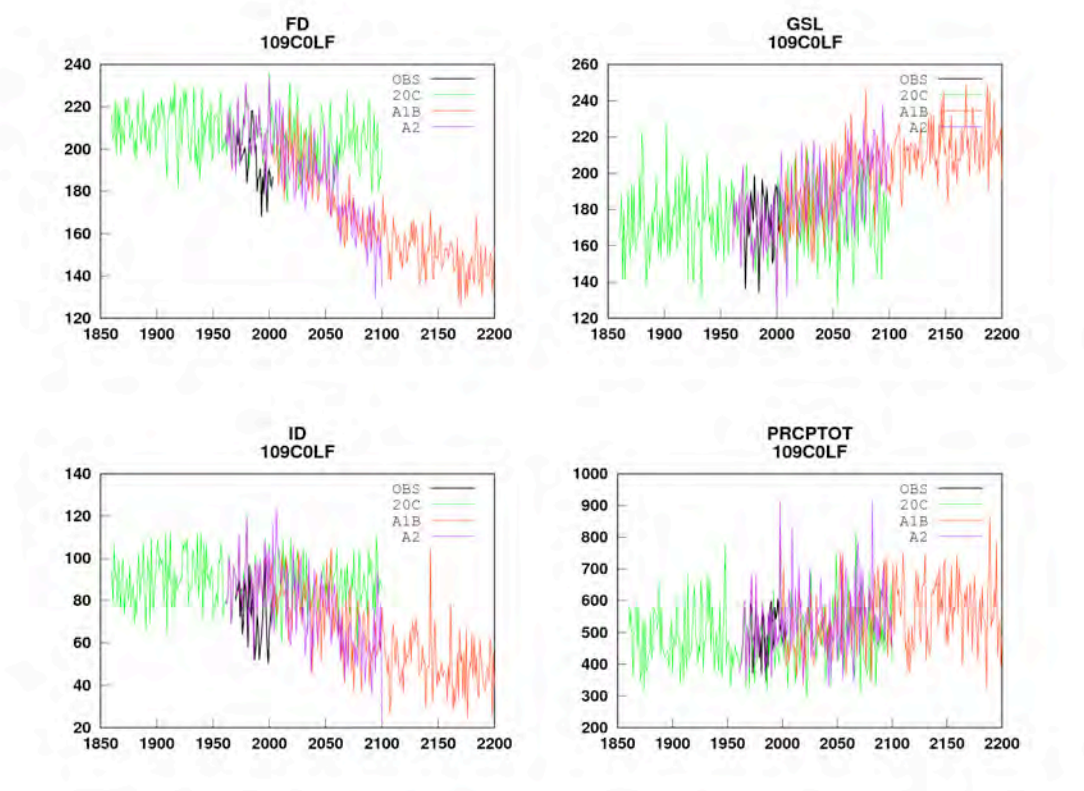


Figure 1a. Annual values of the Climdex indices FD, GSL, ID, and PRCPTOT (see Table 7), for the station Fraser Lake.

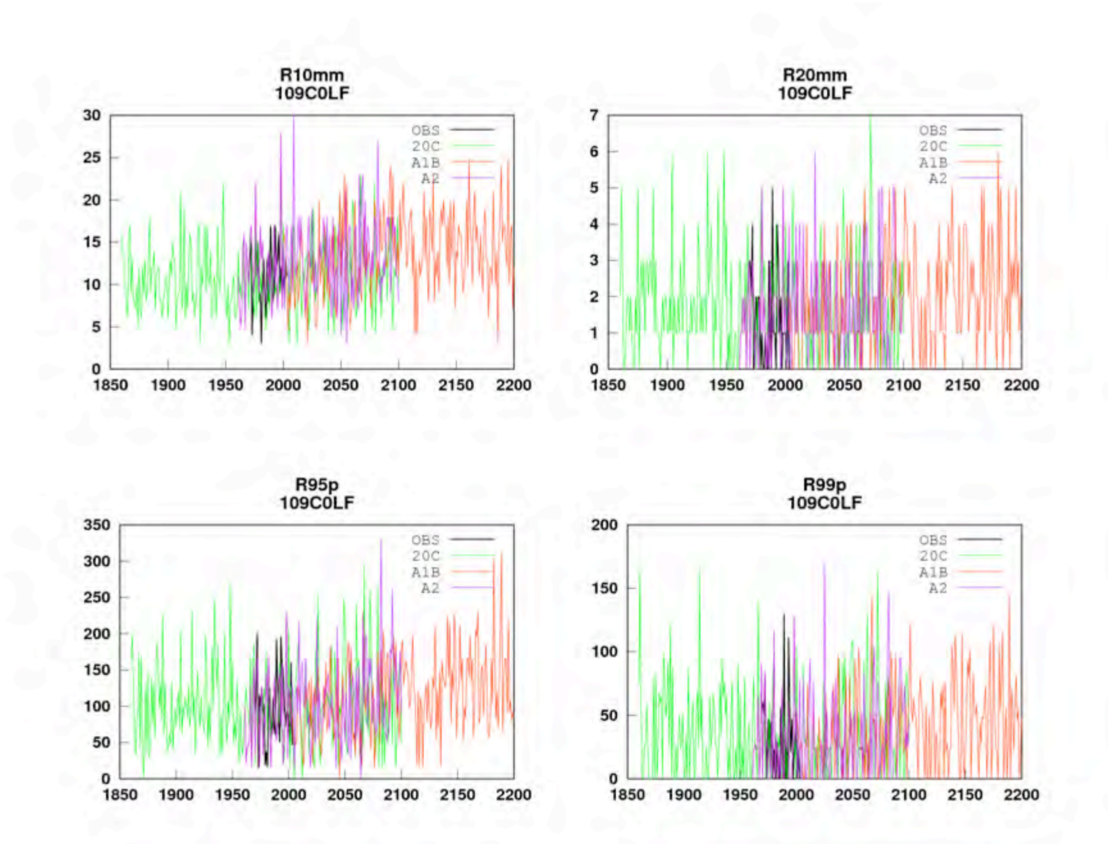


Figure 1b. Like a), for the indices R10, R20, R95p, and R99p.

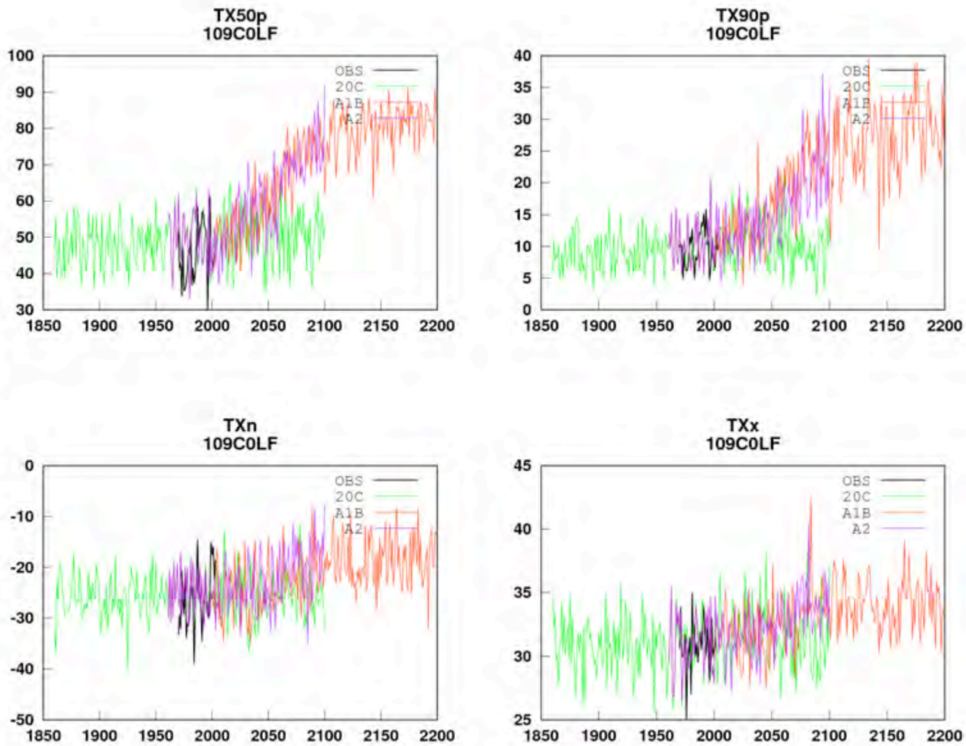


Figure 2. Like Figure 1, for the temperature indices TX50p, TX90p, TXn, and TXx.

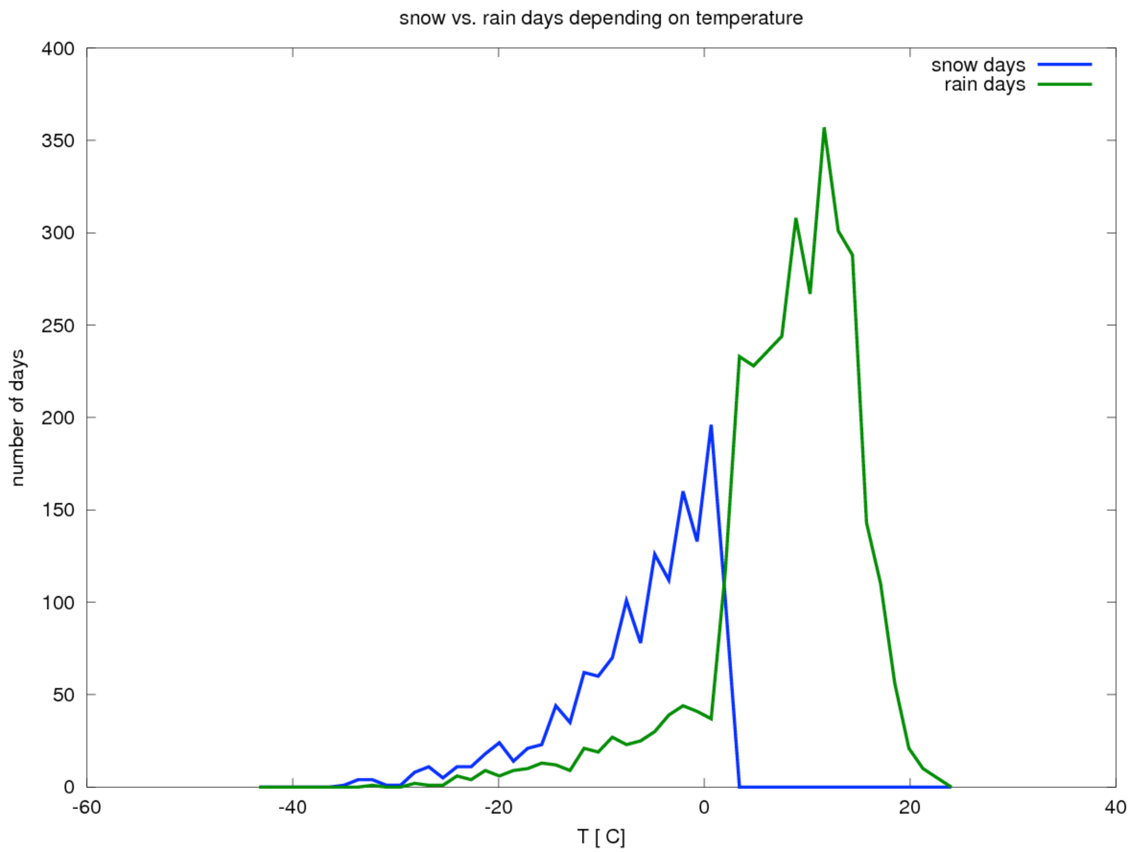


Figure 3. Proxy model used for separating precipitation into rainfall and snowfall events, based on temperature thresholds.

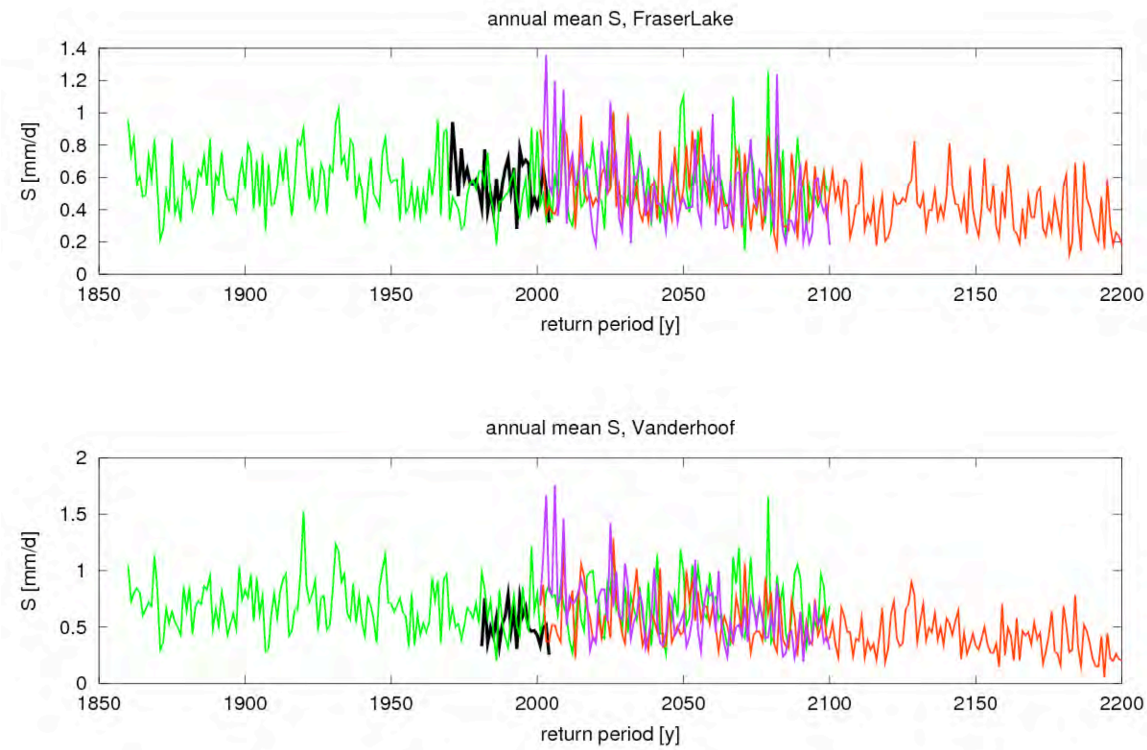


Figure 4a. Annual mean snowfall (proxy) series from downscaled precipitation scenarios.

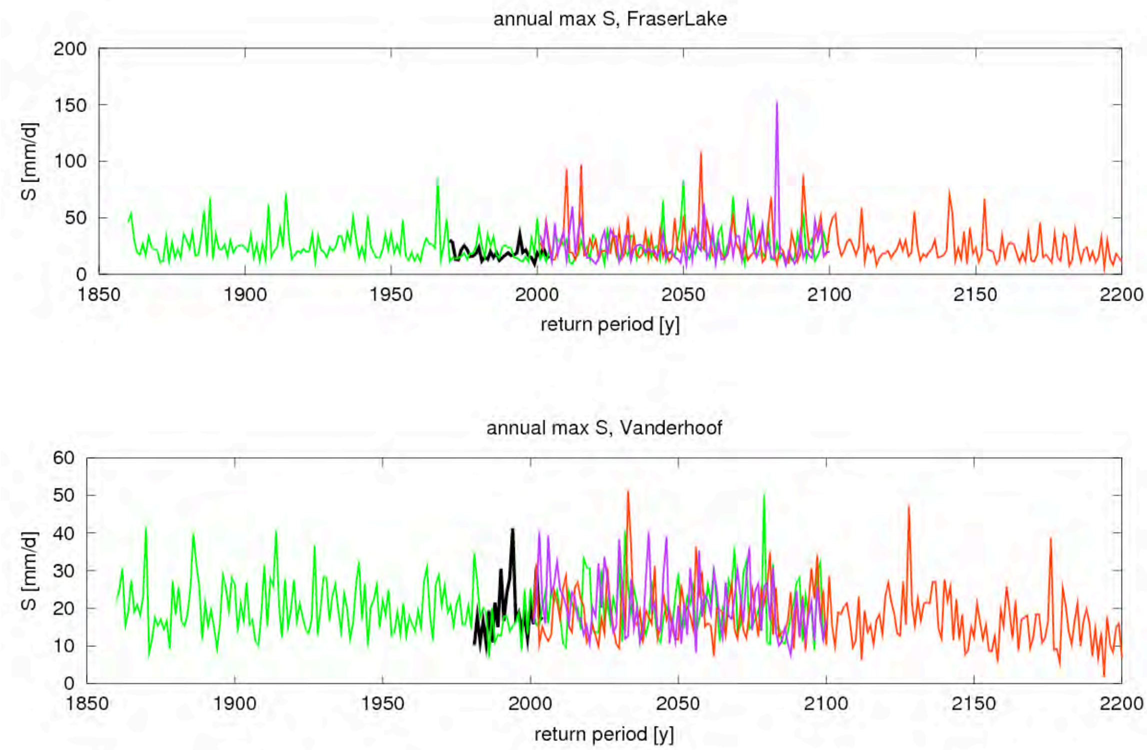


Figure 4b. As Figure 4a, for annual maximum.

Appendix F

Completed Protocol Worksheet 3

No.	Infrastructure Components	Infrastructure Design (bridge, pavement, etc.)	Functionality (capacity, reliability, serviceability)	Drainage (watershed, surface/groundwater)	Maintenance (structure/materials changes)	Emergency Response	Policy / Guidelines / Engineering Standards	Highway Safety	Environmental Effect
		Performance Response Considerations							
	Above Ground								
1	Asphalt - Hot in Place	LT	✓		✓		✓	✓	
2	Asphalt - Seal Coat	LT	✓		✓		✓	✓	
3	Pavement Marking		✓		✓		✓	✓	
4	Shoulders (Including Gravel)	✓	✓	✓	✓	✓	✓	✓	
5	Barriers		✓		✓		✓	✓	
6	Curb - Concrete		✓		✓		✓	✓	
7	Curb - Asphalt		✓		✓		✓	✓	
8	Luminaires		✓			✓	✓	✓	
9	Poles	✓	✓		✓		✓		
10	Signs - Sheeting		✓		✓		✓	✓	
11	Signs - Wood or metal bases	✓	✓		✓		✓	✓	
12	Signage - Side Mounted - Over 3.2 m^2	✓	✓		✓		✓	✓	
13	Signage - Overhead Guide Signs	✓	✓		✓		✓	✓	
14	Overhead Changeable Message Signs – Weigh Scale	✓	✓		✓		✓	✓	
15	Ditches	✓	✓	✓	✓	✓	✓	✓	✓
16	Embankments/Cuts	✓	✓	✓	✓	✓	✓		✓
17	Natural Hillsides	✓	✓	✓		✓	✓		
18	Engineered Stabilization Works								
19	Structures that Cross Streams - Bridges	✓	✓	✓	✓	✓	✓		✓
20	Structures that Cross Roads - Bridges	✓	✓	✓	✓	✓	✓		
21	Railways (Drainage Interaction)	✓	✓	✓	✓	✓	✓		
22	River Training Works - Rip Rap	✓	✓	✓	✓	✓	✓	✓	✓
23	Retaining Walls - MSE Walls								
24	Asphalt Spillway and Associated Piping – Above Ground Elements	✓	✓	✓	✓		✓	✓	✓
	Below Ground								
25	Pavement Structure	✓	✓	✓			✓	✓	
26	Catch Basins	✓	✓	✓	✓		✓	✓	✓
27	Roadway Drainage Appliances	✓	✓	✓	✓		✓	✓	
28	Sub-Drains	✓	✓	✓			✓	✓	
29	Below Ground Third Party Utilities	✓	✓			✓	✓		
30	Above Ground Third Party Utilities	✓	✓			✓	✓		
31	Culverts < 3m	✓	✓	✓	✓	✓	✓	✓	✓
32	Culverts ≥ 3m	✓	✓	✓	✓	✓	✓	✓	✓
33	Piping/Culvert - Below Ground Elements.	✓	✓	✓	✓	✓	✓	✓	✓
	Miscellaneous								
34	Winter Maintenance		✓	✓	✓		✓	✓	✓
35	Habitat Features								
36	Routine Maintenance		✓	✓	✓		✓	✓	
37	Pavement Marking Repair		✓	✓	✓		✓	✓	
38	Pavement / Curb/ Barrier / Sign Repair		✓	✓	✓		✓	✓	

Temperature

No.	Infrastructure Components	1 High Temperature					2 Low Temperature				
		Day(s) with max. temp. exceeding 34.8°C				Can be provide by modifying Climdex indices **Road:** Pavement AC binder type is determined from pavement temp: Vanderhoof area has pavement oil specification for surface high temp of +58°C **Bridge:** Max Mean Daily +24°C for area (design temp from 34°C to 49°C depending on structure: concrete or steel)	Day(s) with min. temp. below -35°C				Can be provide by modifying Climdex indices **Road:** An air temperature of -30°C or somewhat lower is reasonable: in Vanderhoof area the pavement oil specification for surface low temp is -30°C **Bridge:** Min Mean Daily -38°C or -40°C (Design temp Max Min -45°C or -55°C depending on bridge type: concrete, steel)
	Above Ground	Y/N	P	S	R		Y/N	P	S	R	
1	Asphalt - Hot in Place	Y	6	3	18	57 C used for asphalt	Y	6	0	0	
2	Asphalt - Seal Coat	Y	6	1	6	52 to 58 C. May need to upgrade 20 years from now.	Y	6	0	0	
3	Pavement Marking	Y	6	0	0	Annual refurbishment	Y	6	0	0	
4	Shoulders (Including Gravel)	Y	6	0	0	Annual refurbishment					
5	Barriers										
6	Curb - Concrete										
7	Curb - Asphalt	Y	6	0	0		Y	6	0	0	
8	Luminaires										
9	Poles										
10	Signs - Sheeting										
11	Signs - Wood or metal bases										
12	Signage - Side Mounted - Over 3.2 m^2										
13	Signage - Overhead Guide Signs										
14	Overhead Changeable Message Signs – Weigh Scale										
15	Ditches										
16	Embankments/Cuts	Y	6	0	0						
17	Natural Hillsides	Y	6	0	0						
18	Engineered Stabilization Works										
19	Structures that Cross Streams - Bridges	Y	6	4	24	Minor structures designed for 35 C major structures designed to 49 C	Y	6	1	6	
20	Structures that Cross Roads - Bridges	Y	6	4	24	Minor structures designed for 35 C major structures designed to 49 C	Y	6	1	6	
21	Railways (Drainage Interaction)										
22	River Training Works - Rip Rap										
23	Retaining Walls - MSE Walls										
24	Asphalt Spillway and Associated Piping – Above Ground Elements	Y	6	0	0						
	Below Ground										
25	Pavement Structure										
26	Catch Basins										
27	Roadway Drainage Appliances										
28	Sub-Drains						Y	6	0	0	Positive impact
29	Below Ground Third Party Utilities										
30	Above Ground Third Party Utilities										
31	Culverts < 3m						Y	6	0	0	Positive impact
32	Culverts ≥ 3m						Y	6	0	0	Positive impact
33	Piping/Culvert - Below Ground Elements.										
	Miscellaneous										
34	Winter Maintenance						Y	6	1	6	
35	Habitat Features										
36	Routine Maintenance	Y	6	1	6		Y	6	1	6	
37	Pavement Marking Repair										
38	Pavement / Curb/ Barrier / Sign Repair										
		11					11				

No.	Infrastructure Components	3 Average Temperature					4 Temperature Variability				
		Average Maximum Temperature Over 7 Days				Can be provide by modifying Climdex indices	Daily temperature variation of more than 25°C				Can be provided by modifying the Climdex indices **Road:** is reasonable for air temp. For pavement, we use a max variation in pavement temp of 90°C **Bridge:** Bridge: Range for bridge could be either 104°C or -79°C depending on structure type
	Above Ground	Y/N	P	S	R		Y/N	P	S	R	
1	Asphalt - Hot in Place										
2	Asphalt - Seal Coat										
3	Pavement Marking										
4	Shoulders (Including Gravel)										
5	Barriers										
6	Curb - Concrete										
7	Curb - Asphalt										
8	Luminaires										
9	Poles										
10	Signs - Sheeting										
11	Signs - Wood or metal bases										
12	Signage - Side Mounted - Over 3.2 m^2										
13	Signage - Overhead Guide Signs										
14	Overhead Changeable Message Signs – Weigh Scale										
15	Ditches										
16	Embankments/Cuts										
17	Natural Hillsides										
18	Engineered Stabilization Works										
19	Structures that Cross Streams - Bridges										
20	Structures that Cross Roads - Bridges										
21	Railways (Drainage Interaction)										
22	River Training Works - Rip Rap										
23	Retaining Walls - MSE Walls										
24	Asphalt Spillway and Associated Piping – Above Ground Elements										
	Below Ground										
25	Pavement Structure										
26	Catch Basins										
27	Roadway Drainage Appliances										
28	Sub-Drains										
29	Below Ground Third Party Utilities										
30	Above Ground Third Party Utilities										
31	Culverts < 3m										
32	Culverts ≥ 3m										
33	Piping/Culvert - Below Ground Elements.										
	Miscellaneous										
34	Winter Maintenance										
35	Habitat Features										
36	Routine Maintenance										
37	Pavement Marking Repair										
38	Pavement / Curb/ Barrier / Sign Repair										
		0					0				

No.	Infrastructure Components	5 Freeze/Thaw					6 Frost / Frost Penetration				
		Total number of days where max tem > 0 C and min temp < 0 C				This parameter also affects how much frost growth will occur in subsoils under pavement, below foundations etc.	47 or more consecutive days where min. temp. <0°C				Can be provide by modifying Climdex indices. **Road:** Mainly affects how thick the road gravels need to be to deal with frost heaving in the subsoil. (Frost probe data available) (Use frost degree days)
	Above Ground	Y/N	P	S	R		Y/N	P	S	R	
1	Asphalt - Hot in Place	Y	5	1	5	Easy to repair.					
2	Asphalt - Seal Coat	Y	5	1	5	Easy to repair.					
3	Pavement Marking	Y	5	1	5	Easy to repair.					
4	Shoulders (Including Gravel)	Y	5	1	5						
5	Barriers										
6	Curb - Concrete	Y	5	2	10	Could be impacts from salt.					
7	Curb - Asphalt	Y	5	1	5						
8	Luminaires										
9	Poles						Y	6	0		Depth of piles.
10	Signs - Sheeting										
11	Signs - Wood or metal bases										
12	Signage - Side Mounted - Over 3.2 m^2										
13	Signage - Overhead Guide Signs										
14	Overhead Changeable Message Signs – Weigh Scale						Y	6	0		
15	Ditches	Y	5	0	0						
16	Embankments/Cuts	Y	5	1	5						
17	Natural Hillsides	Y	5	1	5						
18	Engineered Stabilization Works										
19	Structures that Cross Streams - Bridges	Y	5	3	15	Salt and corrosion issues potential. Could impact life of structure.	Y	6	0		Structural foundation.
20	Structures that Cross Roads - Bridges	Y	5	3	15	Salt and corrosion issues potential. Could impact life of structure.	Y	6	0		Structural foundation.
21	Railways (Drainage Interaction)										
22	River Training Works - Rip Rap										
23	Retaining Walls - MSE Walls										
24	Asphalt Spillway and Associated Piping – Above Ground Elements	Y	5	2	10						
	Below Ground										
25	Pavement Structure	Y	5	1	5		Y	6	0		
26	Catch Basins	Y	5	2	10						
27	Roadway Drainage Appliances	Y	5	2	10						
28	Sub-Drains	Y	5	1	5	May freeze at outlet.					
29	Below Ground Third Party Utilities										
30	Above Ground Third Party Utilities										
31	Culverts < 3m	Y	5	1	5	Icing of culverts.					Icing of culverts.
32	Culverts ≥ 3m	Y	5	1	5						
33	Piping/Culvert - Below Ground Elements.	Y	5	1	5						
	Miscellaneous										
34	Winter Maintenance	Y	5	4	20		Y	6	0		Black ice susceptibility.
35	Habitat Features										
36	Routine Maintenance	Y	5	3	15						
37	Pavement Marking Repair										
38	Pavement / Curb/ Barrier / Sign Repair										
		21					6				

No.	Infrastructure Components	7 Total Annual Rainfall					8 Extreme High Rainfall					Sust			
		406.7 mm Average 30 year rainfall.				Can be provide by modifying Climdex indices. Based on observed 30 year average total annual rainfall.	> 35 mm rain				Can be provide by modifying Climdex indices Generally not seeing thunderstorms in the area but maybe in the catchment area. May be driven by sustained storms. Some uncertainty here about the cause of the event.	≥ 5 consecutive days with > 3.5 mm rain			
	Above Ground	Y/N	P	S	R		Y/N	P	S	R		Y/N	P	S	R
1	Asphalt - Hot in Place														
2	Asphalt - Seal Coat														
3	Pavement Marking														
4	Shoulders (Including Gravel)						Y	5	4	20		Y	5	3	15
5	Barriers						Y	5	2	10					
6	Curb - Concrete						Y	5	2	10					
7	Curb - Asphalt						Y	5	2	10					
8	Luminaires														
9	Poles														
10	Signs - Sheeting														
11	Signs - Wood or metal bases														
12	Signage - Side Mounted - Over 3.2 m^2														
13	Signage - Overhead Guide Signs														
14	Overhead Changeable Message Signs – Weigh Scale														
15	Ditches	Y	5	2	10		Y	5	4	20		Y	5	1	5
16	Embankments/Cuts	Y	5	2	10		Y	5	4	20		Y	5	3	15
17	Natural Hillsides	Y	5	2	10		Y	5	2	10		Y	5	2	10
18	Engineered Stabilization Works														
19	Structures that Cross Streams - Bridges	Y	5	2	10	Scour	Y	5	3	15	Roadway drainage.	Y	5	2	10
20	Structures that Cross Roads - Bridges						Y	5	3	15	Roadway drainage.	Y	5	2	10
21	Railways (Drainage Interaction)	Y	5	2	10		Y	5	2	10	Meet with railroad to discuss.	Y	5	2	10
22	River Training Works - Rip Rap	Y	5	2	10		Y	5	3	15		Y	5	2	10
23	Retaining Walls - MSE Walls														
24	Asphalt Spillway and Associated Piping – Above Ground Elements	Y	5	2	10		Y	5	5	25		Y	5	2	10
	Below Ground														
25	Pavement Structure	Y	5	2	10	igher potential for soil saturation						Y	5	2	10
26	Catch Basins	Y	5	1	5		Y	5	5	25		Y	5	2	10
27	Roadway Drainage Appliances	Y	5	1	5		Y	5	5	25		Y	5	2	10
28	Sub-Drains	Y	5	1	5		Y	5	2	10		Y	5	2	10
29	Below Ground Third Party Utilities						Y	5	2	10	Potential erosion issues. Tend to run parallel to the road.				
30	Above Ground Third Party Utilities														
31	Culverts < 3m	Y	5	1	5		Y	5	5	25	Design practices are a concern. Used to be based on Rational Method. May be under designed. In filed typically used a standard 600 pipe.	Y	5	3	15
32	Culverts ≥ 3m	Y	5	1	5		Y	5	3	15		Y	5	2	10
33	Piping/Culvert - Below Ground Elements.	Y	5	1	5		Y	5	4	20		Y	5	2	10
	Miscellaneous														
34	Winter Maintenance						Y	5	4	20	Functionality issues in winter. May need some follow-up.				
35	Habitat Features														
36	Routine Maintenance						Y	5	5	25		Y	5	2	10
37	Pavement Marking Repair														
38	Pavement / Curb/ Barrier / Sign Repair														
		14					21					17			

	Precipitation as Rain															
	9	10					11					12				
Infrastructure Components	tained Rainfall	Longer Sustained Rainfall					Low Rainfall					Prolonged Dry Periods (Drought)				
	Can be provide by modifying Climdex indices Trigger adjusted from 25 mm.	≥ 23 consecutive days with > 0.3 mm rain				Can be provide by modifying Climdex indices Trigger adjusted from 10 mm rain.	≥ 10 consecutive days with precipitation < 0.2 mm				Provided by PCIC	≥ 24 consecutive days with precipitation < 0.2 mm				Deemed to be out of scope.
Above Ground		Y/N	P	S	R		Y/N	P	S	R		Y/N	P	S	R	
1 Asphalt - Hot in Place																
2 Asphalt - Seal Coat																
3 Pavement Marking																
4 Shoulders (Including Gravel)	Soil saturation.															
5 Barriers																
6 Curb - Concrete																
7 Curb - Asphalt																
8 Luminaires																
9 Poles																
10 Signs - Sheeting																
11 Signs - Wood or metal bases																
12 Signage - Side Mounted - Over 3.2 m^2																
13 Signage - Overhead Guide Signs																
14 Overhead Changeable Message Signs – Weigh Scale																
15 Ditches																
16 Embankments/Cuts	Erosion. Weeping.															
17 Natural Hillsides																
18 Engineered Stabilization Works																
19 Structures that Cross Streams - Bridges																
20 Structures that Cross Roads - Bridges																
21 Railways (Drainage Interaction)																
22 River Training Works - Rip Rap																
23 Retaining Walls - MSE Walls																
24 Asphalt Spillway and Associated Piping – Above Ground Elements																
Below Ground																
25 Pavement Structure																
26 Catch Basins																
27 Roadway Drainage Appliances																
28 Sub-Drains																
29 Below Ground Third Party Utilities																
30 Above Ground Third Party Utilities																
31 Culverts < 3m	Soil saturation concerns.															
32 Culverts ≥ 3m																
33 Piping/Culvert - Below Ground Elements.																
Miscellaneous																
34 Winter Maintenance																
35 Habitat Features																
36 Routine Maintenance																
37 Pavement Marking Repair																
38 Pavement / Curb/ Barrier / Sign Repair																
		0					0					0				

	Precipitation as Snow										Combined Events									
	13					14					15					16				
Infrastructure Components	Snow (Frequency)					Snow Accumulation					Snow Storm/ Blizzard					Rain / Snow /Wind				
	Days with snow fall > 10 cm				Some model information provided by PCIC	5 or more consecutive days with a snow depth >60cm				Some model information provided by PCIC. Hydrology issues dealt with in parameter 24.	8 or more days with blowing snow				May be able to develop this with models.	Rain on Snow Including Temperature and Wind Speed				Rain is the issue.
Above Ground	Y/N	P	S	R		Y/N	P	S	R		Y/N	P	S	R		Y/N	P	S	R	
1 Asphalt - Hot in Place																				
2 Asphalt - Seal Coat																				
3 Pavement Marking																				
4 Shoulders (Including Gravel)																				
5 Barriers																				
6 Curb - Concrete																				
7 Curb - Asphalt																				
8 Luminaires																				
9 Poles																				
10 Signs - Sheeting																				
11 Signs - Wood or metal bases																				
12 Signage - Side Mounted - Over 3.2 m^2																				
13 Signage - Overhead Guide Signs																				
14 Overhead Changeable Message Signs – Weigh Scale																				
15 Ditches																				
16 Embankments/Cuts																				
17 Natural Hillsides																				
18 Engineered Stabilization Works																				
19 Structures that Cross Streams - Bridges																				
20 Structures that Cross Roads - Bridges																				
21 Railways (Drainage Interaction)																				
22 River Training Works - Rip Rap																				
23 Retaining Walls - MSE Walls																				
24 Asphalt Spillway and Associated Piping – Above Ground Elements																				
Below Ground																				
25 Pavement Structure																				
26 Catch Basins																				
27 Roadway Drainage Appliances																				
28 Sub-Drains																				
29 Below Ground Third Party Utilities																				
30 Above Ground Third Party Utilities																				
31 Culverts < 3m																				
32 Culverts ≥ 3m																				
33 Piping/Culvert - Below Ground Elements.																				
Miscellaneous																				
34 Winter Maintenance	Y	2	1	2							Y	2	0							
35 Habitat Features																				
36 Routine Maintenance																				
37 Pavement Marking Repair	Y	2	0	0							Y	2	0							
38 Pavement / Curb/ Barrier / Sign Repair	Y	2	1	2							Y	2	0							
	3					0					3					0				

	Combined Events												
	17					18							
Infrastructure Components	Rain on Snow					Hail / Sleet					Rai		
	Days with Rain on Snow				Model information provided by PCIC	Days with Precipitation Falling as Ice Particles				Cannot be done with models.	P > 6 mm/3h Surface Temperature <0 No snowfall		
Above Ground	Y/N	P	S	R		Y/N	P	S	R		Y/N	P	S
1 Asphalt - Hot in Place													
2 Asphalt - Seal Coat													
3 Pavement Marking													
4 Shoulders (Including Gravel)													
5 Barriers													
6 Curb - Concrete													
7 Curb - Asphalt													
8 Luminaires											Y	3	0
9 Poles											Y	3	0
10 Signs - Sheeting													
11 Signs - Wood or metal bases											Y	3	0
12 Signage - Side Mounted - Over 3.2 m^2											Y	3	0
13 Signage - Overhead Guide Signs											Y	3	0
14 Overhead Changeable Message Signs – Weigh Scale											Y	3	0
15 Ditches	Y	4	2	8									
16 Embankments/Cuts	Y	4	2	8									
17 Natural Hillsides	Y	4	2	8									
18 Engineered Stabilization Works													
19 Structures that Cross Streams - Bridges	Y	4	2	8							Y	3	1
20 Structures that Cross Roads - Bridges	Y	4	2	8							Y	3	1
21 Railways (Drainage Interaction)	Y	4	2	8							Y	3	0
22 River Training Works - Rip Rap													
23 Retaining Walls - MSE Walls													
24 Asphalt Spillway and Associated Piping – Above Ground Elements	Y	4	3	12							Y	3	1
Below Ground													
25 Pavement Structure													
26 Catch Basins	Y	4	3	12		Y	3	0	0		Y	3	2
27 Roadway Drainage Appliances	Y	4	3	12		Y	3	0	0		Y	3	2
28 Sub-Drains	Y	4	1	4									
29 Below Ground Third Party Utilities											Y	3	0
30 Above Ground Third Party Utilities											Y	3	2
31 Culverts < 3m	Y	4	3	12		Y	3	1	3				
32 Culverts ≥ 3m	Y	4	1	4									
33 Piping/Culvert - Below Ground Elements.	Y	4	3	12									
Miscellaneous													
34 Winter Maintenance	Y	4	4	16							Y	3	5
35 Habitat Features													
36 Routine Maintenance											Y	3	1
37 Pavement Marking Repair													
38 Pavement / Curb/ Barrier / Sign Repair													
	14					3					16		

Infrastructure Specific Events

#	Infrastructure Components	19		20					21					22				
		in on Frozen Ground		Freezing Rain					Visibility					High Wind/ Downburst				
		°C	Some model information provided by PCIC. Potential drainage issues.	9 or more days with rain that falls as liquid and freezes on contact				Cannot be done with models	≥ 15 hours per year with visibility < 1,000 m				Can be provide by modifying Climdex indices	Three hour periods ≥ 63 km/hr				Some model information provided by PCIC Bridge: Burns Lake 1:10 = 305Pa = 80km/hr 1:25 = 355Pa = 87km/hr 1:50 = 390Pa = 91km/hr
	Above Ground	R		Y/N	P	S	R		Y/N	P	S	R		Y/N	P	S	R	
1	Asphalt - Hot in Place																	
2	Asphalt - Seal Coat																	
3	Pavement Marking																	
4	Shoulders (Including Gravel)																	
5	Barriers																	
6	Curb - Concrete																	
7	Curb - Asphalt																	
8	Luminaires	0												Y	2	**0**	0	
9	Poles	0												Y	2	**1**	2	
10	Signs - Sheeting													Y	2	**0**	0	
11	Signs - Wood or metal bases	0												Y	2	**0**	0	
12	Signage - Side Mounted - Over 3.2 m^2	0												Y	2	**2**	4	
13	Signage - Overhead Guide Signs	0												Y	2	**2**	4	
14	Overhead Changeable Message Signs – Weigh Scale	0												Y	2	**2**	4	
15	Ditches																	
16	Embankments/Cuts																	
17	Natural Hillsides																	
18	Engineered Stabilization Works																	
19	Structures that Cross Streams - Bridges	3												Y	3	**0**	**0**	
20	Structures that Cross Roads - Bridges	3												Y	3	**0**	**0**	
21	Railways (Drainage Interaction)	0																
22	River Training Works - Rip Rap																	
23	Retaining Walls - MSE Walls																	
24	Asphalt Spillway and Associated Piping – Above Ground Elements	3																
	Below Ground																	
25	Pavement Structure																	
26	Catch Basins	6																
27	Roadway Drainage Appliances	6																
28	Sub-Drains																	
29	Below Ground Third Party Utilities	0																
30	Above Ground Third Party Utilities	6	Potential for failure on to highway. Above ground wires, etc.															
31	Culverts < 3m																	
32	Culverts ≥ 3m																	
33	Piping/Culvert - Below Ground Elements.																	
	Miscellaneous																	
34	Winter Maintenance	15												Y	2	**2**	4	
35	Habitat Features																	
36	Routine Maintenance	3												Y	2	**2**	4	
37	Pavement Marking Repair																	
38	Pavement / Curb/ Barrier / Sign Repair																	
				0					0					11				

#	Infrastructure Components	23					24					25					26				
		Rapid Snow Melt					Snowmelt Driven Peak Flow Events (Spring Freshette)					Ice / Ice Jams					Ground Freezing				
		snm > 9 mm/3h				Some model information provided by PCIC.											Number of Days Below -5 °C				
	Above Ground	Y/N	P	S	R		Y/N	P	S	R		Y/N	P	S	R		Y/N	P	S	R	
1	Asphalt - Hot in Place																Y	6	2	12	
2	Asphalt - Seal Coat																Y	6	2	12	
3	Pavement Marking																				
4	Shoulders (Including Gravel)																				
5	Barriers																				
6	Curb - Concrete																				
7	Curb - Asphalt																				
8	Luminaires																				
9	Poles																				
10	Signs - Sheeting																				
11	Signs - Wood or metal bases																				
12	Signage - Side Mounted - Over 3.2 m^2																				
13	Signage - Overhead Guide Signs																				
14	Overhead Changeable Message Signs – Weigh Scale																				
15	Ditches	Y	4	3	12																
16	Embankments/Cuts	Y	4	4	16																
17	Natural Hillsides	Y	4	3	12																
18	Engineered Stabilization Works																				
19	Structures that Cross Streams - Bridges	Y	4	1	4		Y	5	**3**	15		Y	3	2	6	High clearance. Some piers in the water					
20	Structures that Cross Roads - Bridges																				
21	Railways (Drainage Interaction)	Y	4	2	8		Y	5	**2**	10											
22	River Training Works - Rip Rap	Y	4	1	4		Y	5	**3**	15		Y	3	2	6						
23	Retaining Walls - MSE Walls																				
24	Asphalt Spillway and Associated Piping – Above Ground Elements	Y	4	2	8																
	Below Ground																				
25	Pavement Structure																Y	6	1	6	
26	Catch Basins	Y	4	2	8																
27	Roadway Drainage Appliances	Y	4	2	8																
28	Sub-Drains																				
29	Below Ground Third Party Utilities																				
30	Above Ground Third Party Utilities																				
31	Culverts < 3m	Y	4	4	16		Y	5	**5**	25		Y	3	3	9	Has not been a problem in the past. May be a concern in the future.					
32	Culverts ≥ 3m	Y	4	1	4		Y	5	**4**	20		Y	3	3	9						
33	Piping/Culvert - Below Ground Elements.	Y	4	2	8																
	Miscellaneous																				
34	Winter Maintenance	Y	4	1	4							Y	3	3	9						
35	Habitat Features																				
36	Routine Maintenance	Y	4	1	8																
37	Pavement Marking Repair																				
38	Pavement / Curb/ Barrier / Sign Repair																				
		14					5					5					3				

Appendix G

Sensitivity Analysis

Performance Response Considerations

#	Infrastructure Components	Infrastructure Design (bridge, pavement, etc.)	Functionality (capacity, reliability, serviceability)	Drainage (watershed, surface/groundwater)	Maintenance (structure/materials changes)	Emergency Response	Policy / Guidelines / Engineering Standards	Highway Safety	Environmental Effect
	Above Ground								
1	Asphalt - Hot in Place	LT	✓		✓		✓	✓	
2	Asphalt - Seal Coat	LT	✓		✓		✓	✓	
3	Pavement Marking		✓		✓		✓	✓	
4	Shoulders (Including Gravel)	✓	✓	✓	✓	✓	✓	✓	
5	Barriers		✓		✓		✓	✓	
6	Curb - Concrete		✓		✓		✓	✓	
7	Curb - Asphalt		✓		✓		✓	✓	
8	Luminaires		✓			✓	✓	✓	
9	Poles	✓	✓		✓		✓		
10	Signs - Sheeting		✓		✓		✓	✓	
11	Signs - Wood or metal bases	✓	✓		✓		✓	✓	
12	Signage - Side Mounted - Over 3.2 m^2	✓	✓		✓		✓	✓	
13	Signage - Overhead Guide Signs	✓	✓		✓		✓	✓	
14	Overhead Changeable Message Signs – Weigh Scale	✓	✓		✓		✓	✓	
15	Ditches	✓	✓	✓	✓	✓	✓	✓	✓
16	Embankments/Cuts	✓	✓	✓	✓	✓	✓		✓
17	Natural Hillsides	✓	✓	✓		✓	✓		
18	Engineered Stabilization Works								
19	Structures that Cross Streams - Bridges	✓	✓	✓	✓	✓	✓		✓
20	Structures that Cross Roads - Bridges	✓	✓	✓	✓	✓	✓		
21	Railways (Drainage Interaction)	✓	✓	✓	✓	✓	✓		
22	River Training Works - Rip Rap	✓	✓	✓	✓	✓	✓	✓	✓
23	Retaining Walls - MSE Walls								
24	Asphalt Spillway and Associated Piping – Above Ground Elements	✓	✓	✓	✓		✓	✓	✓
	Below Ground								
25	Pavement Structure	✓	✓	✓			✓	✓	
26	Catch Basins	✓	✓	✓	✓		✓	✓	✓
27	Roadway Drainage Appliances	✓	✓	✓	✓		✓	✓	
28	Sub-Drains	✓	✓	✓			✓	✓	
29	Below Ground Third Party Utilities	✓	✓			✓	✓		
30	Above Ground Third Party Utilities	✓	✓			✓	✓		
31	Culverts < 3m	✓	✓	✓	✓	✓	✓	✓	✓
32	Culverts ≥ 3m	✓	✓	✓	✓	✓	✓	✓	✓
33	Piping/Culvert - Below Ground Elements.	✓	✓	✓	✓	✓	✓	✓	✓
	Miscellaneous								
34	Winter Maintenance		✓	✓	✓		✓	✓	✓
35	Habitat Features								
36	Routine Maintenance		✓	✓	✓		✓	✓	
37	Pavement Marking Repair		✓	✓	✓		✓	✓	
38	Pavement / Curb/ Barrier / Sign Repair		✓	✓	✓		✓	✓	

Temperature

#	Infrastructure Components	1 High Temperature					2 Low Temperature				
		Day(s) with max. temp. exceeding 34.8°C				Can be provide by modifying Climdex indices **Road:** Pavement AC binder type is determined from pavement temp: Vanderhoof area has pavement oil specification for surface high temp of +58°C **Bridge:** Max Mean Daily +24°C for area (design temp from 34°C to 49°C depending on structure: concrete or steel)	Day(s) with min. temp. below -35°C				Can be provide by modifying Climdex indices **Road:** An air temperature of -30°C or somewhat lower is reasonable: in Vanderhoof area the pavement oil specification for surface low temp is -30°C **Bridge:** Min Mean Daily -38°C or -40°C (Design temp Max Min -45°C or -55°C depending on bridge type: concrete, steel)
	Above Ground	Y/N	P	S	R		Y/N	P	S	R	
1	Asphalt - Hot in Place	Y	6	3	18	57 C used for asphalt	Y	6	0	0	
2	Asphalt - Seal Coat	Y	6	1	6	52 to 58 C. May need to upgrade 20 years from now.	Y	6	0	0	
3	Pavement Marking	Y	6	0	0	Annual refurbishment	Y	6	0	0	
4	Shoulders (Including Gravel)	Y	6	0	0	Annual refurbishment					
5	Barriers										
6	Curb - Concrete										
7	Curb - Asphalt	Y	6	0	0		Y	6	0	0	
8	Luminaires										
9	Poles										
10	Signs - Sheeting										
11	Signs - Wood or metal bases										
12	Signage - Side Mounted - Over 3.2 m^2										
13	Signage - Overhead Guide Signs										
14	Overhead Changeable Message Signs – Weigh Scale										
15	Ditches										
16	Embankments/Cuts	Y	6	0	0						
17	Natural Hillsides	Y	6	0	0						
18	Engineered Stabilization Works										
19	Structures that Cross Streams - Bridges	Y	6	4	24	Minor structures designed for 35 C major structures designed to 49 C	Y	6	1	6	
20	Structures that Cross Roads - Bridges	Y	6	4	24	Minor structures designed for 35 C major structures designed to 49 C	Y	6	1	6	
21	Railways (Drainage Interaction)										
22	River Training Works - Rip Rap										
23	Retaining Walls - MSE Walls										
24	Asphalt Spillway and Associated Piping – Above Ground Elements	Y	6	0	0						
	Below Ground										
25	Pavement Structure										
26	Catch Basins										
27	Roadway Drainage Appliances										
28	Sub-Drains						Y	6	0	0	Positive impact
29	Below Ground Third Party Utilities										
30	Above Ground Third Party Utilities										
31	Culverts < 3m						Y	6	0	0	Positive impact
32	Culverts ≥ 3m						Y	6	0	0	Positive impact
33	Piping/Culvert - Below Ground Elements.										
	Miscellaneous										
34	Winter Maintenance						Y	6	1	6	
35	Habitat Features										
36	Routine Maintenance	Y	6	1	6		Y	6	1	6	
37	Pavement Marking Repair										
38	Pavement / Curb/ Barrier / Sign Repair										
		11					11				

#	Infrastructure Components	3 Average Temperature					4 Temperature Variability				
		Average Maximum Temperature Over 7 Days				Can be provide by modifying Climdex indices	Daily temperature variation of more than 25°C				Can be provided by modifying the Climdex indices **Road:** is reasonable for air temp. For pavement, we use a max variation in pavement temp of 90°C **Bridge:** Bridge: Range for bridge could be either 104°C or -79°C depending on structure type
	Above Ground	Y/N	P	S	R		Y/N	P	S	R	
1	Asphalt - Hot in Place										
2	Asphalt - Seal Coat										
3	Pavement Marking										
4	Shoulders (Including Gravel)										
5	Barriers										
6	Curb - Concrete										
7	Curb - Asphalt										
8	Luminaires										
9	Poles										
10	Signs - Sheeting										
11	Signs - Wood or metal bases										
12	Signage - Side Mounted - Over 3.2 m^2										
13	Signage - Overhead Guide Signs										
14	Overhead Changeable Message Signs – Weigh Scale										
15	Ditches										
16	Embankments/Cuts										
17	Natural Hillsides										
18	Engineered Stabilization Works										
19	Structures that Cross Streams - Bridges										
20	Structures that Cross Roads - Bridges										
21	Railways (Drainage Interaction)										
22	River Training Works - Rip Rap										
23	Retaining Walls - MSE Walls										
24	Asphalt Spillway and Associated Piping – Above Ground Elements										
	Below Ground										
25	Pavement Structure										
26	Catch Basins										
27	Roadway Drainage Appliances										
28	Sub-Drains										
29	Below Ground Third Party Utilities										
30	Above Ground Third Party Utilities										
31	Culverts < 3m										
32	Culverts ≥ 3m										
33	Piping/Culvert - Below Ground Elements.										
	Miscellaneous										
34	Winter Maintenance										
35	Habitat Features										
36	Routine Maintenance										
37	Pavement Marking Repair										
38	Pavement / Curb/ Barrier / Sign Repair										
		0					0				

#	Infrastructure Components	5 Freeze/Thaw					6 Frost / Frost Penetration				
		Total number of days where max tem > 0 C and min temp < 0 C				This parameter also affects how much frost growth will occur in subsoils under pavement, below foundations etc.	47 or more consecutive days where min. temp. <0°C				Can be provide by modifying Climdex indices. **Road:** Mainly affects how thick the road gravels need to be to deal with frost heaving in the subsoil. (Frost probe data available) (Use frost degree days)
	Above Ground	Y/N	P	S	R		Y/N	P	S	R	
1	Asphalt - Hot in Place	Y	5	1	5	Easy to repair.					
2	Asphalt - Seal Coat	Y	5	1	5	Easy to repair.					
3	Pavement Marking	Y	5	1	5	Easy to repair.					
4	Shoulders (Including Gravel)	Y	5	1	5						
5	Barriers										
6	Curb - Concrete	Y	5	2	10	Could be impacts from salt.					
7	Curb - Asphalt	Y	5	1	5						
8	Luminaires										
9	Poles						Y	6	0		Depth of piles.
10	Signs - Sheeting										
11	Signs - Wood or metal bases										
12	Signage - Side Mounted - Over 3.2 m^2										
13	Signage - Overhead Guide Signs										
14	Overhead Changeable Message Signs – Weigh Scale						Y	6	0		
15	Ditches	Y	5	0	0						
16	Embankments/Cuts	Y	5	1	5						
17	Natural Hillsides	Y	5	1	5						
18	Engineered Stabilization Works										
19	Structures that Cross Streams - Bridges	Y	5	3	15	Salt and corrosion issues potential. Could impact life of structure.	Y	6	0		Structural foundation.
20	Structures that Cross Roads - Bridges	Y	5	3	15	Salt and corrosion issues potential. Could impact life of structure.	Y	6	0		Structural foundation.
21	Railways (Drainage Interaction)										
22	River Training Works - Rip Rap										
23	Retaining Walls - MSE Walls										
24	Asphalt Spillway and Associated Piping – Above Ground Elements	Y	5	2	10						
	Below Ground										
25	Pavement Structure	Y	5	1	5		Y	6	0		
26	Catch Basins	Y	5	2	10						
27	Roadway Drainage Appliances	Y	5	2	10						
28	Sub-Drains	Y	5	1	5	May freeze at outlet.					
29	Below Ground Third Party Utilities										
30	Above Ground Third Party Utilities										
31	Culverts < 3m	Y	5	1	5	Icing of culverts.					Icing of culverts.
32	Culverts ≥ 3m	Y	5	1	5						
33	Piping/Culvert - Below Ground Elements.	Y	5	1	5						
	Miscellaneous										
34	Winter Maintenance	Y	5	4	20		Y	6	0		Black ice susceptibility.
35	Habitat Features										
36	Routine Maintenance	Y	5	3	15						
37	Pavement Marking Repair										
38	Pavement / Curb/ Barrier / Sign Repair										
		21					6				

#	Infrastructure Components	7 Total Annual Rainfall					8 Extreme High Rainfall					Sust			
		406.7 mm Average 30 year rainfall.				Can be provide by modifying Climdex indices. Based on observed 30 year average total annual rainfall.	> 35 mm rain				Can be provide by modifying Climdex indices Generally not seeing thunderstorms in the area but maybe in the catchment area. May be driven by sustained storms. Some uncertainty here about the cause of the event.	≥ 5 consecutive days with > 3.5 mm rain			
	Above Ground	Y/N	P	S	R		Y/N	P	S	R		Y/N	P	S	R
1	Asphalt - Hot in Place														
2	Asphalt - Seal Coat														
3	Pavement Marking														
4	Shoulders (Including Gravel)						Y	5	4	20		Y	5	3	15
5	Barriers						Y	5	2	10					
6	Curb - Concrete						Y	5	2	10					
7	Curb - Asphalt						Y	5	2	10					
8	Luminaires														
9	Poles														
10	Signs - Sheeting														
11	Signs - Wood or metal bases														
12	Signage - Side Mounted - Over 3.2 m^2														
13	Signage - Overhead Guide Signs														
14	Overhead Changeable Message Signs – Weigh Scale														
15	Ditches	Y	5	2	10		Y	5	4	20		Y	5	1	5
16	Embankments/Cuts	Y	5	2	10		Y	5	4	20		Y	5	3	15
17	Natural Hillsides	Y	5	2	10		Y	5	2	10		Y	5	2	10
18	Engineered Stabilization Works														
19	Structures that Cross Streams - Bridges	Y	5	2	10	Scour	Y	5	3	15	Roadway drainage.	Y	5	2	10
20	Structures that Cross Roads - Bridges						Y	5	3	15	Roadway drainage.	Y	5	2	10
21	Railways (Drainage Interaction)	Y	5	2	10		Y	5	2	10	Meet with railroad to discuss.	Y	5	2	10
22	River Training Works - Rip Rap	Y	5	2	10		Y	5	3	15		Y	5	2	10
23	Retaining Walls - MSE Walls														
24	Asphalt Spillway and Associated Piping – Above Ground Elements	Y	5	2	10		Y	5	5	25		Y	5	2	10
	Below Ground														
25	Pavement Structure	Y	5	2	10	igher potential for soil saturation						Y	5	2	10
26	Catch Basins	Y	5	1	5		Y	5	5	25		Y	5	2	10
27	Roadway Drainage Appliances	Y	5	1	5		Y	5	5	25		Y	5	2	10
28	Sub-Drains	Y	5	1	5		Y	5	2	10		Y	5	2	10
29	Below Ground Third Party Utilities						Y	5	2	10	Potential erosion issues. Tend to run parallel to the road.				
30	Above Ground Third Party Utilities														
31	Culverts < 3m	Y	5	1	5		Y	5	5	25	Design practices are a concern. Used to be based on Rational Method. May be under designed. In filed typically used a standard 600 pipe.	Y	5	3	15
32	Culverts ≥ 3m	Y	5	1	5		Y	5	3	15		Y	5	2	10
33	Piping/Culvert - Below Ground Elements.	Y	5	1	5		Y	5	4	20		Y	5	2	10
	Miscellaneous														
34	Winter Maintenance						Y	5	4	20	Functionality issues in winter. May need some follow-up.				
35	Habitat Features														
36	Routine Maintenance						Y	5	5	25		Y	5	2	10
37	Pavement Marking Repair														
38	Pavement / Curb/ Barrier / Sign Repair														
		14					21					17			

Precipitation as Rain (columns 9–12)

Infrastructure Components	9 tained Rainfall	10 Longer Sustained Rainfall					11 Low Rainfall					12 Prolonged Dry Periods (Drought)				
	Can be provide by modifying Climdex indices Trigger adjusted from 25 mm.	≥ 23 consecutive days with > 0.3 mm rain				Can be provide by modifying Climdex indices Trigger adjusted from 10 mm rain.	≥ 10 consecutive days with precipitation < 0.2 mm				Provided by PCIC	≥ 24 consecutive days with precipitation < 0.2 mm				Deemed to be out of scope.
Above Ground		Y/N	P	S	R		Y/N	P	S	R		Y/N	P	S	R	
1 Asphalt - Hot in Place																
2 Asphalt - Seal Coat																
3 Pavement Marking																
4 Shoulders (Including Gravel)	Soil saturation.															
5 Barriers																
6 Curb - Concrete																
7 Curb - Asphalt																
8 Luminaires																
9 Poles																
10 Signs - Sheeting																
11 Signs - Wood or metal bases																
12 Signage - Side Mounted - Over 3.2 m^2																
13 Signage - Overhead Guide Signs																
14 Overhead Changeable Message Signs – Weigh Scale																
15 Ditches																
16 Embankments/Cuts	Erosion. Weeping.															
17 Natural Hillsides																
18 Engineered Stabilization Works																
19 Structures that Cross Streams - Bridges																
20 Structures that Cross Roads - Bridges																
21 Railways (Drainage Interaction)																
22 River Training Works - Rip Rap																
23 Retaining Walls - MSE Walls																
24 Asphalt Spillway and Associated Piping – Above Ground Elements																
Below Ground																
25 Pavement Structure																
26 Catch Basins																
27 Roadway Drainage Appliances																
28 Sub-Drains																
29 Below Ground Third Party Utilities																
30 Above Ground Third Party Utilities																
31 Culverts < 3m	Soil saturation concerns.															
32 Culverts ≥ 3m																
33 Piping/Culvert - Below Ground Elements.																
Miscellaneous																
34 Winter Maintenance																
35 Habitat Features																
36 Routine Maintenance																
37 Pavement Marking Repair																
38 Pavement / Curb/ Barrier / Sign Repair																
		0					0					0				

Precipitation as Snow (columns 13–14) / Combined Events (columns 15–16)

Infrastructure Components	13 Snow (Frequency)					14 Snow Accumulation					15 Snow Storm/ Blizzard					16 Rain / Snow /Wind				
	Days with snow fall > 10 cm				Some model information provided by PCIC	5 or more consecutive days with a snow depth >60cm				Some model information provided by PCIC. Hydrology issues dealt with in parameter 24.	8 or more days with blowing snow				May be able to develop this with models.	Rain on Snow Including Temperature and Wind Speed				Rain is the issue.
Above Ground	Y/N	P	S	R		Y/N	P	S	R		Y/N	P	S	R		Y/N	P	S	R	
1 Asphalt - Hot in Place																				
2 Asphalt - Seal Coat																				
3 Pavement Marking																				
4 Shoulders (Including Gravel)																				
5 Barriers																				
6 Curb - Concrete																				
7 Curb - Asphalt																				
8 Luminaires																				
9 Poles																				
10 Signs - Sheeting																				
11 Signs - Wood or metal bases																				
12 Signage - Side Mounted - Over 3.2 m^2																				
13 Signage - Overhead Guide Signs																				
14 Overhead Changeable Message Signs – Weigh Scale																				
15 Ditches																				
16 Embankments/Cuts																				
17 Natural Hillsides																				
18 Engineered Stabilization Works																				
19 Structures that Cross Streams - Bridges																				
20 Structures that Cross Roads - Bridges																				
21 Railways (Drainage Interaction)																				
22 River Training Works - Rip Rap																				
23 Retaining Walls - MSE Walls																				
24 Asphalt Spillway and Associated Piping – Above Ground Elements																				
Below Ground																				
25 Pavement Structure																				
26 Catch Basins																				
27 Roadway Drainage Appliances																				
28 Sub-Drains																				
29 Below Ground Third Party Utilities																				
30 Above Ground Third Party Utilities																				
31 Culverts < 3m																				
32 Culverts ≥ 3m																				
33 Piping/Culvert - Below Ground Elements.																				
Miscellaneous																				
34 Winter Maintenance	Y	2	1	2							Y	2	0							
35 Habitat Features																				
36 Routine Maintenance																				
37 Pavement Marking Repair	Y	2	0	0							Y	2	0							
38 Pavement / Curb/ Barrier / Sign Repair	Y	2	1	2							Y	2	0							
	3					0					3					0				

Combined Events (columns 17–19)

Infrastructure Components	17 Rain on Snow					18 Hail / Sleet					Ra		
	Days with Rain on Snow				Model information provided by PCIC	Days with Precipitation Falling as Ice Particles				Cannot be done with models.	P > 6 mm/3h Surface Temperature <0 No snowfall		
Above Ground	Y/N	P	S	R		Y/N	P	S	R		Y/N	P	S
1 Asphalt - Hot in Place													
2 Asphalt - Seal Coat													
3 Pavement Marking													
4 Shoulders (Including Gravel)													
5 Barriers													
6 Curb - Concrete													
7 Curb - Asphalt													
8 Luminaires											Y	4	0
9 Poles											Y	4	0
10 Signs - Sheeting													
11 Signs - Wood or metal bases											Y	4	0
12 Signage - Side Mounted - Over 3.2 m^2											Y	4	0
13 Signage - Overhead Guide Signs											Y	4	0
14 Overhead Changeable Message Signs – Weigh Scale											Y	4	0
15 Ditches	Y	4	2	8									
16 Embankments/Cuts	Y	4	2	8									
17 Natural Hillsides	Y	4	2	8									
18 Engineered Stabilization Works													
19 Structures that Cross Streams - Bridges	Y	4	2	8							Y	4	1
20 Structures that Cross Roads - Bridges	Y	4	2	8							Y	4	1
21 Railways (Drainage Interaction)	Y	4	2	8							Y	4	0
22 River Training Works - Rip Rap													
23 Retaining Walls - MSE Walls													
24 Asphalt Spillway and Associated Piping – Above Ground Elements	Y	4	3	12							Y	4	1
Below Ground													
25 Pavement Structure													
26 Catch Basins	Y	4	3	12		Y	3	0	0		Y	4	2
27 Roadway Drainage Appliances	Y	4	3	12		Y	3	0	0		Y	4	2
28 Sub-Drains	Y	4	1	4									
29 Below Ground Third Party Utilities											Y	4	0
30 Above Ground Third Party Utilities											Y	4	2
31 Culverts < 3m	Y	4	3	12		Y	3	1	3				
32 Culverts ≥ 3m	Y	4	1	4									
33 Piping/Culvert - Below Ground Elements.	Y	4	3	12									
Miscellaneous													
34 Winter Maintenance	Y	4	4	16							Y	2	5
35 Habitat Features													
36 Routine Maintenance											Y	4	1
37 Pavement Marking Repair													
38 Pavement / Curb/ Barrier / Sign Repair													
	14					**3**					**16**		

Infrastructure Specific Events

	Infrastructure Components	19		20					21					22					23					24					25					26				
		in on Frozen Ground		Freezing Rain					Visibility					High Wind/ Downburst					Rapid Snow Melt					Snowmelt Driven Peak Flow Events (Spring Freshette)					Ice / Ice Jams					Ground Freezing				
		°C	Some model information provided by PCIC. Potential drainage issues.	**9 or more days with rain that falls as liquid and freezes on contact**				Cannot be done with models	**≥ 15 hours per year with visibility < 1,000 m**				Can be provide by modifying Climdex indices	**Three hour periods ≥ 63 km/hr**				Some model information provided by PCIC Bridge: Burns Lake 1:10 = 305Pa = 80km/hr 1:25 = 355Pa = 87km/hr 1:50 = 390Pa = 91km/hr	**snm > 9 mm/3h**				Some model information provided by PCIC.											**Number of Days Below -5 °C**				
	Above Ground	R		Y/N	P	S	R		Y/N	P	S	R		Y/N	P	S	R		Y/N	P	S	R		Y/N	P	S	R		Y/N	P	S	R		Y/N	P	S	R	
1	Asphalt - Hot in Place																																	Y	6	1	6	Adjusted S down to test severity score. Marginally medium risk.
2	Asphalt - Seal Coat																																	Y	6	1	6	Adjusted S down to test severity score. Marginally medium risk.
3	Pavement Marking																																					
4	Shoulders (Including Gravel)																																					
5	Barriers																																					
6	Curb - Concrete																																					
7	Curb - Asphalt																																					
8	Luminaires	0												Y	2	0	0																					
9	Poles	0												Y	2	1	2																					
10	Signs - Sheeting													Y	2	0	0																					
11	Signs - Wood or metal bases	0												Y	2	0	0																					
12	Signage - Side Mounted - Over 3.2 m^2	0												Y	2	2	4																					
13	Signage - Overhead Guide Signs	0												Y	2	2	4																					
14	Overhead Changeable Message Signs – Weigh Scale	0												Y	2	2	4																					
15	Ditches																		Y	4	3	12																
16	Embankments/Cuts																		Y	4	4	16																
17	Natural Hillsides																		Y	4	3	12																
18	Engineered Stabilization Works																																					
19	Structures that Cross Streams - Bridges	4												Y	3	0	0		Y	4	1	4		Y	5	3	15		Y	4	2	8	High clearance. Some piers in the water					
20	Structures that Cross Roads - Bridges	4												Y	3	0	0																					
21	Railways (Drainage Interaction)	0																	Y	4	2	8		Y	5	2	10											
22	River Training Works - Rip Rap																		Y	4	1	4		Y	5	3	15		Y	4	2	8						
23	Retaining Walls - MSE Walls																																					
24	Asphalt Spillway and Associated Piping – Above Ground Elements	4																	Y	4	2	8																
	Below Ground																																					
25	Pavement Structure																																	Y	6	1	6	
26	Catch Basins	8																	Y	4	2	8																
27	Roadway Drainage Appliances	8																	Y	4	2	8																
28	Sub-Drains																																					
29	Below Ground Third Party Utilities	0																																				
30	Above Ground Third Party Utilities	8	Potential for failure on to highway. Above ground wires, etc.																																			
31	Culverts < 3m																		Y	4	4	16		Y	5	5	25		Y	4	3	12	Has not been a problem in the past. May be a concern in the future.					
32	Culverts ≥ 3m																		Y	4	1	4		Y	5	4	20		Y	4	3	12						
33	Piping/Culvert - Below Ground Elements.																		Y	4	2	8																
	Miscellaneous																																					
34	Winter Maintenance	10	Adjusted severity score down. Maringally medium risk.											Y	2	2	4		Y	4	1	4							Y	4	3	12						
35	Habitat Features																																					
36	Routine Maintenance	4												Y	2	2	4		Y	4	1	8																
37	Pavement Marking Repair																																					
38	Pavement / Curb/ Barrier / Sign Repair																																					
				0					0					11					14					5					5					3				

Appendix H

Completed Protocol Worksheet 4

Worksheet 4 – Engineering Analysis

In this step the practitioner will determine the relationship between the Performance Responses loads placed on the infrastructure and its capacity. Vulnerability exists when infrastructure has insufficient capacity to withstand the effects placed on it. Resiliency exits when the infrastructure has sufficient capacity to withstand increasing climate change effects.

8.4.4 Calculation of Total Load (L_T)

Basis of Determination:

- **Definitions;**
- **Direct measurements;**
- **Engineering calculations; or**
- **Assumptions based on professional judgement.**

Infrastructure Component (from 8.3.4 from Work Sheet 3)	8.4.1 Existing Load State Basis of Determination L_E	8.4.2 Climate Load State Basis of Determination L_C	8.4.3 Other Change Load State Basis of Determination L_O	8.4.4 Total Load $L_T = L_E+L_C+L_O$
Catch Basins & Extreme Rainfall over 24 Hours (mm)				
2050s	29.3	4.5	0	33.8
2100s	29.3	12.1	0	41.4
Basis for Determination ☞	We assumed these structures were originally designed for a 1:5 year return period. Referencing the 1:5 year return period to 24 hour rainfall data from the Rainfall Frequency Atlas for Canada (HOGG, 1985) yields rainfall as 29.3 mm / 24 hour for the Vanderhoof area. This is the unfactored design load used for comparison.	The future peak rainfall event will likely increase in frequency, but the change in magnitude is unknown. Therefore we assumed the climate load will equal to the average increase of the A1B and A2 models. The average increase in the 24 hour extreme rainfall with return period of 1:5 year are 15.2% (4.5mm / 24 hour) and 41.3% (12.1 mm / 24 hour) for the 2050's and 2100's scenarios, respectively. The increase for the 2100's scenario may be higher due to higher uncertainty in the model. However we assumed that would be considered in the model results already.	Land use changes (logging, pine beetle) could increase amounts of water but we assume little affect on this structure as it is part of the internal road drainage and likely not affected by the watershed.	
Culverts ≤ 3 m & Extreme Rainfall over One Day (mm/24hr)				
2050s	45	7	4.5	56.5
2100s	45	24.3	4.5	73.8
Basis for Determination ☞	We assumed these structures were originally designed for a 1:100 year return period.	The results from the climate models (A1B and A2) were used to evaluate the climate load. The average increase in the 24 hour extreme rainfall with return period of 1:100 year are 15.5% (7 mm / 24 hour) and 54% (24.3 mm / 24 hour) for the 2050's and 2100's scenarios, respectively.	Parts of the forest in this area were affected by pine beetle infestation. However the forest will likely grow back in the future. Therefore the effects of pine beetle will likely become less significant for the 2050's and 2100's scenarios.	

Worksheet 4 – Engineering Analysis

Concrete Bridges & Extreme High Temperature (°C)	Referencing the 1:100 year return period to 24 hour rainfall data from the Rainfall Frequency Atlas for Canada (HOGG, 1985) yields rainfall as 45 mm / 24 hour for the Vanderhoof area. This is the unfactored design load used for comparison.	The increase for the 2100's scenario may be higher due to higher uncertainty in the model. However we assumed that would be considered in the model results already.	The surface vegetation may also change due to logging, forest fires, land development, etc. Such activities could increase the load by increasing surface runoff. We assume a 10% (4.5 mm / 24 hour) increase in load.	
2050s	34.8	0.9		35.7
2100s	34.8	2.7		37.5
Basis for Determination ☞	For high temp indicator for structures in area used 34.8°C (though some temp spikes up to 45°C)	The averages of results from the two climate models (A1B and A2) were used to evaluate the climate load. The average increases in high temperature with return period of 1:50 year are 2.56% and 7.69% for the 2050's and 2100's scenarios, respectively.		
		The increase for the 2100's scenario may be higher due to higher uncertainty in the model. However we assumed that would be considered in the model results already.		
Concrete Bridges & Extreme Low Temperature (°C)				
2050s	-47	-1.8		-48.8
2100s	-47	-6.4		-53.4
Basis for Determination ☞	Lowest temperature found in Vanderhoof in 1984	The averages of results from the two climate models (A1B and A2) were used to evaluate the climate load. The average decrease in low temperature with return period of 1:50 year are -3.72% and -13.59% for the 2050's and 2100's scenarios, respectively.		

Worksheet 4 – Engineering Analysis

8.4.8 Calculation of Total Capacity (C_T)

$C_T = C_E + C_M + C_A$

Where: C_T = Total capacity of the infrastructure
C_E = Existing capacity of the infrastructure
C_M = Maturing capacity of the infrastructure
C_A = Additional capacity of the infrastructure

Basis of Determination
- Definitions;
- Direct measurements;
- Engineering calculations; or
- Assumptions based on professional judgement.

Infrastructure Component (from section 8.3.4 of Work Sheet 3)	8.4.5 Existing Capacity State Basis of Determination C_E	8.4.6 Maturing Capacity State Basis of Determination C_M	8.4.7 Additional Capacity State Basis of Determination C_A	8.4.8 Total Capacity $C_T = C_E+C_M+C_A$
Catch Basins & Extreme Rainfall over 24 Hours				
2050s	29.3	0	1.5	27.8
2100s	29.3	0	1.5	27.8
Basis for Determination ☞	We cannot verify if the designers added capacity as a safety factor to this component. Also due to lack of weather data prior to the time of construction in the 1960's, we cannot verify if there have been changes to climate condition.	No increase was used for this component.	Maturing or degradation of the culverts could reduce the capacity by 5% (1.5 mm / 24 hour). Maintenance will be required when the culverts are blocked by debris and whenever necessary.	
Culverts ≤ 3 m & Extreme Rainfall over One Day				
2050s	45	0	-2.3	42.8
2100s	45	0	-2.3	42.8
Basis for Determination ☞	We cannot verify if the designers added capacity as a safety factor to this component. Also due to lack of weather data prior to the time of construction in the 1960's, we cannot verify if there have been changes to climate condition.	No reduction was used for this component. Maintenance will be required when the culverts are blocked by debris and whenever necessary.	Maturing or degradation of the culverts could reduce the capacity by 5% (2.3 mm / 24 hour).	
Concrete Bridges & Extreme High Temperature (°C)				
2050s	34.4			34.4
2100s	34.4			34.4
Basis for Determination ☞	Bridges built late 1960's early 1970's. In 1970's bridges were designed according to: For Steel max temp 120°F = 49°C. For Concrete take average temp of 59°F (15°C) and for cold climates go to a rise of 35°F = 94°F (34.4°C). (Standards - Thermal Forces section: the range is "figured from an assumed temperature at the time of erection." We used 59°F as the assumed temp for standard today is 15°C.). Citation: Standard Specifications for Highway Bridges: Adopted by the American Association of State Highway Officials, Tenth Ed. 1969, p. 25.			
Concrete Bridges & Extreme Low Temperature (°C)				
2050s	-45			-45
2100s	-45			-45
Basis for Determination ☞	Bridges built late 1960's early 1970's. Using the current bridge design standards: Using Max and Min average daily temperatures from an iso-temperature map. For Steel structures use max min and decrease by 15°C to get -55°C For Concrete take max min average temp of 40°F and decrease by 5°C to get -45°C. Citation: Canadian Highway Bridge Design Code, CSA, Nov 2006			

Worksheet 4 – Engineering Analysis

8.4.9 Evaluate Vulnerability (V_R)

$$V_R = \frac{L_T}{C_T}$$

Where:

V_R = Vulnerability Ratio
L_T = Total load on the infrastructure
C_T = Total capacity of the infrastructure

Infrastructure Component		Total Load (from 8.4.4)	Total Capacity (from 8.4.8)	$V_R = \frac{L_T}{C_T}$ Vulnerability
Catch Basins & Extreme Rainfall over 24 Hours				
	2050s	33.8	27.8	1.21
	2100s	41.4	27.8	1.49
Culverts ≤ 3 m & Extreme Rainfall over One Day				
	2050s	56.6	42.8	1.32
	2100s	73.8	42.8	1.73
Concrete Bridges & Extreme High Temperature				
	2050s	35.7	34.4	1.04
	2100s	37.5	34.4	1.09
Concrete Bridges & Extreme Low Temperature				
	2050s	-48.8	-45	1.08
	2100s	-53.4	-45	1.19

When $V_R > 1$, the infrastructure component is vulnerable

Infrastructure Component showing vulnerability should be forwarded to Section 8.5.2 in Work Sheet 5 for STEP 5 Recommendation Evaluation.

Worksheet 4 – Engineering Analysis

8.4.10 Calculate Capacity Deficit (C_D)

$C_D = L_T – C_T$

$= L_T – (C_E + C_M + C_A)$

Where:
C_D = Capacity deficit of the infrastructure component
C_T = Total capacity of the infrastructure
L_T = Total load on the infrastructure component
C_E = Existing capacity of the infrastructure component
C_M = Maturing capacity of the infrastructure component
C_A = Additional capacity of the infrastructure component

Infrastructure Component		Total Load (from 8.4.4)	Total Capacity (from 8.4.8)	Capacity Deficit $C_D = L_T – C_T$
Catch Basins & Extreme Rainfall over 24 Hours				
	2050s	33.8	27.8	5.92
	2100s	41.4	27.8	13.57
Culverts ≤ 3 m & Extreme Rainfall over One Day				
	2050s	56.5	42.8	13.73
	2100s	73.8	42.8	31.05
Concrete Bridges & Extreme High Temperature				
	2050s	35.7	34.4	1.29
	2100s	37.5	34.4	3.08
Concrete Bridges & Extreme Low Temperature				
	2050s	-48.8	-45	-3.75
	2100s	-53.4	-45	-8.39

Clarification
The Capacity Deficit is the amount of capacity that must be added to the infrastructure component to address the vulnerability identified by this procedure. The capacity deficit may be addressed by capacity addition projects or through infrastructure management practices.

Worksheet 4 – Engineering Analysis

8.4.11 Data Sufficiency	
Identify process to develop data, Where insufficient	
Issue	**Process**
This analysis gives relative comparisons and is not absolute because of the nature of available data. This analysis gives a relative ranking in broad terms and indicates areas to examine in more detail. Therefore, further study is required.	**Require a detailed study of weather and storm data, time of concentraion, IDF data, structural design specification and maintenance records to determine the capacity of the existing highway drainage. If more storms are predicted then how will infrastructure perform under changing weather conditions.**
Analyzing the climate data to evaluate extreme rain can be an issue as many duration and intensity event combinations can cause problems for structures. Depending on the Time of Concentration, storms of various intensities (i.e. 15 min./2hrs/6hrs/etc.) are required for complete analysis .	**Require a detailed study of weather and storm data, time of concentraion, IDF data, structural design specification and maintenance records to determine the capacity of the existing highway drainage. If more storms are predicted then how will infrastructure perform under changing weather conditions.**
Need to determine if there is a built-in design reserve capacity in the drainage structures .	**Recommend doing a back calculation type of study using a consultant to assess a section(s) of the Coq to determine the original (or changed) design parameters and the actual drainage capacity required for a thorough Step 4 analysis.**

Where data cannot be developed, identify the data gap as a finding in Step 5 of the Protocol – Recommendations.

List Data Gap as findings to be sent to STEP 5 (Worksheet 5: Section 8.5.2)

1. Recommend that contractors document weather conditions (rainfall, wind, etc. from nearest station)that caused major mainenance issues. So link up infrastructure problems with climate data for future monitoring of this interaction.	2. Recommend that if remidial action is required because of this type of analysis that contractors and replace infrastructure with upgraded design as regular maintenance allows and not as a separate program - unless serious situation exists.	3. UBC etc. Have models that predict infrastructure failures - do they have climate as a variable and could this be modeled for MoTI purposes.	4. BCMoT should evaluate pavement grade design and bridge design standards. It would be useful to consider future forecast climate (temperatures) for the lifespan of the structure, rather than rely on historical climate parameters such as minimum and maximum mean daily temperatures as is currently used.

Conclusions

High intensity rainfall events could overload drainage infrastructure:
- Surface ponding on roadway surfaces could impedee emergency response
- Increased rainfall intensity may require updated policies and procedures regarding design and maintenance of highway structures
-

Date:	07-Mar-11
Prepared by:	Joel R. Nodelman on belhaf of BCMoT

Summary of Ross Creek vulnerability analysis for culvert < 3m

Ross Creek Watershed properties

Drainage area = $10km^2$
Vegetation is mostly forest that has been affected by pine beetle infestation
There are minor logging, land development, and agricultural activities

Total load calculation

Existing load (L_E)	Ministry of Environment regional peak flow map	$3m^3/s$
	Regional analysis of nearby WSC gauging station	$4.9m^3/s$
	Regional analysis from Obedkoff's report	$4.9m^3/s$
	Rational method	$5.5m^3/s$
		$L_E \approx 4.6m^3/s$
Climate load (L_C) for year 2050	A1B → 3% increase load	$0.1m^3/s$
	A2 → 28% increase load	$1.3m^3/s$
		$L_C = 0.7m^3/s$
Climate load (L_C) for year 2100	A1B → 25% increase load	$1.2m^3/s$
	A2 → 83% increase load	$3.8m^3/s$
		$L_C = 2.5m^3/s$
Other change load (L_O)	~ 10% increase load due to changes in watershed such as logging, pine beetle, forest fire, and land development.	$0.5m^3/s$
		$L_O = 0.5m^3/s$
Total load (L_T)	**$L_T = L_E + L_C + L_O$**	**$L_T = 5.8m^3/s$ for year 2050** **$L_T = 7.6m^3/s$ for year 2100**

Ross Creek Culvert properties

Approximate maximum slope interpolated from contour map = 2%
Minimum required slope from BC Supplement to TAC = 0.5%
Capacity criteria (HW/D = 1.0)
Culvert size = 1.2m
Culvert length = 18m
Manning's roughness coefficient = 0.022

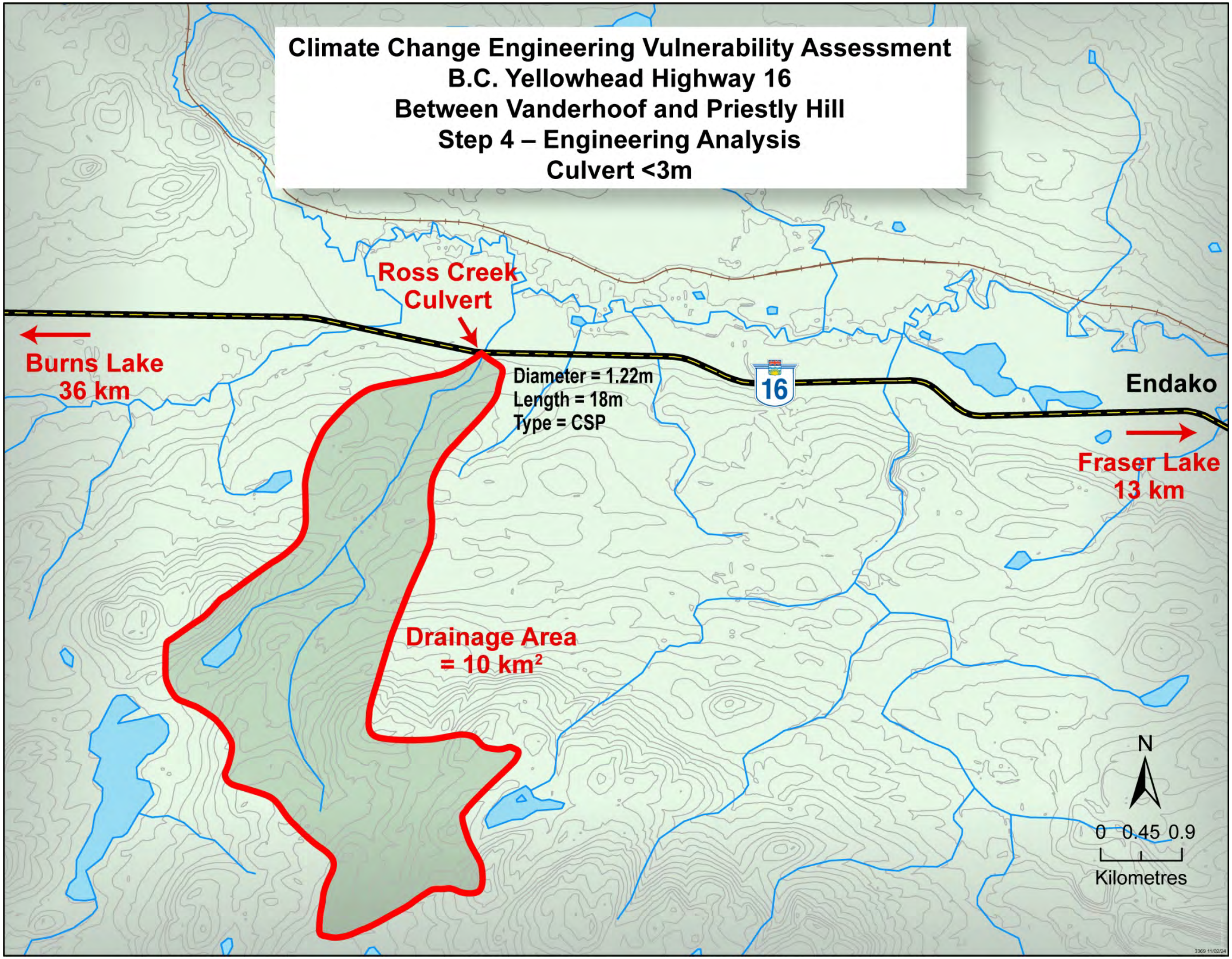
Total capacity calculation

Existing capacity (C_E)	Slope = 0.5%	$2.2m^3/s$
	Slope = 0.75%	$2.3m^3/s$
	Slope = 1%	$2.4m^3/s$
	Slope = 1.25%	$2.5m^3/s$
	Slope = 1.5%	$2.5m^3/s$
	Slope = 1.75%	$2.5m^3/s$
	Slope = 2%	$2.5m^3/s$
	Note: Return period in the order of 1 in 10 to 20 year Critical slope at ≈ 1.5% Maximum capacity for inlet control = $2.5m^3/s$	$C_E \approx 2.2m^3/s$ to $2.5m^3/s$
Adapted capacity (C_A)	There was no modification to the original culvert capacity	$0m^3/s$
		$C_A = 0m^3/s$
Other change capacity (C_M)	~ 5% reduction due to maturing or degradation	$-0.1m^3/s$
		$C_M = -0.1m^3/s$
Total capacity	**$C_T = C_E + C_A + C_M$**	**$C_T = 2.1m^3/s$ to $2.4m^3/s$**

(C_T)	

Vulnerability and Capacity Deficit

Vulnerability (V_R)	$V_R = L_T / C_T$	V_R = 2.4 to 2.8 for year 2050 V_R = 3.2 to 3.6 for year 2100
Capacity Deficit (C_D)	$C_D = L_T - C_T$	C_D = 3.4m^3/s to 3.7m^3/s C_D = 5.2m^3/s to 5.5m^3/s
Minimum size of culvert for replacement	Existing load = 4.6m^3/s	≈ 1.8m
	Future load for year 2050 = 5.8m^3/s	≈ 2.0m
	Future load for year 2100 = 7.6m^3/s	≈ 2.2m
	Note: Approximate size for new culvert, subject to change with detail study.	


Climate Change Engineering Vulnerability Assessment
B.C. Yellowhead Highway 16
Between Vanderhoof and Priestly Hill
Step 4 – Engineering Analysis
Culvert <3m
Ross Creek Culvert
Diameter = 1.22m
Length = 18m
Type = CSP
Burns Lake 36 km
16
Endako
Fraser Lake 13 km
Drainage Area = 10 km²
N
0 0.45 0.9
Kilometres

Appendix I

Completed Protocol Worksheet 5

Worksheet 5 Recommendations

8.5.1 State Limitations	
MAJOR ASSUMPTIONS[1]	The assessment was not limited by the project definition or stated timeframe. The highway is subjected to ongoing maintenance that would tend to mitigate many of the identified climate change risks as practices typically evolve to accommodate current conditions.
Available Infrastructure Information and Sources	The assessment was not limited by lack of technical information regarding the highway. The team had access to personal files and very deep experience with the design, operation and maintenance of the highway.
Available Climate Data and Information	**Unresolved Climate Parameters** PCIC was unable to provide model-based data for three climate parameters during the timeframe of the study. These included: • Rain on Frozen Ground • Ice / Ice Jams • Ground Freezing The risk assessment for these parameters was completed through the application of sensitivity analysis. **Visibility** The team determined that this issue requires more study to define how visibility issues arise currently on the highway. Once BCMoT has developed a better definition of current visibility issues, they will be better placed to assess the impact of climate change on this matter.
Available Other Change Information and Sources	The assessment was not limited by lack of information regarding other sources of change. The experience of the team, and observations of day-to-day operation of the highway compensate for any gaps that may otherwise occur.
Use Of Generic/Specific Examples to Represent Population	This approach was not used in the assessment.
Uncertainty and Related Concepts	Climate modeling is based on inherent assumptions regarding likely emissions scenarios. Additionally, there is a significant level of statistical uncertainty associated with both the modeling and the analytical approaches used to downscale the information generated by the regional climate models to local conditions. PCIC addressed this concern by correlating model predictions with observed, baseline, climate conditions. The BCMoT team possesses a significant level of understanding of the regional climate based on many years of day-to-day, hands-on, experience with the design, operation and maintenance of the highway. This experience provided the team with sufficient foundation to assess the veracity of the climate model projections.
Other	N/A

[1] Notionally, these are the same major assumptions that underlie the entire assessment as determined in Step 1 and Step 2 of this Protocol. They may include boundary conditions used to define the study area, time frame, refurbishment schedules, etc.

Worksheet 5 Recommendations

8.5.2 Recommendations			
Showing Vulnerability from Combination Interactions Assessments (from Work Sheet 3: 8.3.3, Risk = High) **Showing Vulnerability from Engineering Assessment** (from Work Sheet 4: 8.4.9, V_R >1 **Report on Data Gaps** (from Worksheets 1-4: 8.1.7, 8.2.8, 8.3.11, 8.4.11)	**Remedial Engineering Action**	**Management Action**	**Additional Study Required**
Higher Rainfall Higher levels of anticipated rainfall present a significant risk to the infrastructure in terms of drainage management issues. These can adversely affect the safety and serviceability of the infrastructure. The infrastructure is already exhibiting vulnerability to high intensity rainfall events. Thus, the team concluded that these issues may be exacerbated by climate change and raise greater challenges to the ongoing operation and maintenance of the highway.	1. BCMoT should investigate current design reserve capacity of the Yellowhead Highway to handle changing hydrology from increased local extreme rainfall events. 2. If, due to study findings, infrastructure components require upgrading to accommodate increased rainfall intensity, this should be accomplished as a part of regular design and maintenance activities and not as a separate program - unless a serious situation is identified (as forecast changes are 40+ years into future).	3. BCMoT should require contractors to document weather conditions that caused major maintenance issues. Notionally, this would include meteorological data on rainfall, wind, etc. from the nearest weather station. This would link infrastructure problems with climate data and facilitate future monitoring of this interaction. 4. Investigate if University of British Columbia (or other) infrastructure failure models contemplate climate as a variable and if this can be adapted to BCMoT's needs.	5. Develop relevant parameters to measure the interaction between infrastructure design and climate changes (as inputs to methodology and modeling). Specifically, use downscale analysis (of Regional Climate Model data) to determine local climate condition changes and match this with design standards of the particular infrastructure under study. (E.g. changing duration and amount of rainfall within localized area and current design return period.) This will allow a systematic measurement basis for analysis (may require more complex engineering model use in future, such as, continuous rainfall analysis, etc.). 6. Further analysis on the vulnerability of culverts < 3m is recommended due to the uncertainties in the climate models and lack of survey information. At critical locations, it may be necessary to do a detail assessment based on the watershed settings and site conditions. 7. Further assessment is recommended for the Ross Creek culvert to determine if upgrade or

Worksheet 5 Recommendations

8.5.2 Recommendations			
Showing Vulnerability from Combination Interactions Assessments (from Work Sheet 3: 8.3.3, Risk = High) **Showing Vulnerability from Engineering Assessment** (from Work Sheet 4: 8.4.9, V_R >1 **Report on Data Gaps** (from Worksheets 1-4: 8.1.7, 8.2.8, 8.3.11, 8.4.11)	**Remedial Engineering Action**	**Management Action**	**Additional Study Required**
			retrofit will be required even to handle the existing load.
Higher Temperatures The analysis of the interaction between extreme high temperature and bridges indicated that bridge design on this section of highway is relatively robust with respect to temperature. Vulnerability indicators suggest that there might be a marginally small vulnerability relating to concrete bridges. However, the value of the indicator is so close to unity that it would be difficult to argue that this is a material level of risk. In support of this conclusion, the capacity deficit for this interaction was also marginally greater than unity.	N/A	8. BCMoT should monitor the impact of extreme high temperature on concrete bridge structures.	9. There appears to be no immediate need for action on this matter. However, should ongoing monitoring indicate a potential problem, BCMoT should initiate a detailed engineering study of this matter.
Unresolved Climate Parameters PCIC was unable to provide model-based data for three climate parameters during the timeframe of the study. These included: • Rain on Frozen Ground, • Ice / Ice Jams, and • Ground Freezing.	N/A	N/A	10. Although the team concluded that the results generated by the sensitivity analysis are relatively robust, through more advanced statistical downscaling work, BCMoT should pursue better definition of: • Rain on Frozen Ground, • Ice / Ice Jams, and • Ground Freezing.
Visibility Poor visibility can lead to serious safety concerns on the highway. A large portion of serious accidents report fog as a cause. There are multiple causes of fog, including: • Very localized, from warm air	N/A	N/A	11. BCMoT should conduct more study into visibility issues to define how these issues arise currently on the highway. 12. Once BCMoT has developed a better definition of current visibility issues, they

Worksheet 5 Recommendations

8.5.2 Recommendations			
Showing Vulnerability from Combination Interactions Assessments (from Work Sheet 3: 8.3.3, Risk = High) **Showing Vulnerability from Engineering Assessment** (from Work Sheet 4: 8.4.9, V_R >1 **Report on Data Gaps** (from Worksheets 1-4: 8.1.7, 8.2.8, 8.3.11, 8.4.11)	**Remedial Engineering Action**	**Management Action**	**Additional Study Required**
over snow; • Valley fog; or • Low clouds. The team agreed that this is a potentially high-risk item and has identified this issue as a matter for further study. Ultimately, this issue may require the development of specialized highway management strategies.			should assess the impact of climate change on this matter.
Data Management This study proved the advantage of having good data available to the assessment team. The team comprised of experts with extensive knowledge of the highway and the local climate. It would be advantageous to accumulate relevant climate and infrastructure information in a centralized location. In addition to technical design and operational data, there will be benefits from accumulating relevant climate and meteorological data in the same data room. For future assessments, the assessment team would have all relevant information immediately available. Similarly, data rooms could be established for the other highway segments contemplated for vulnerability assessment.	N/A	13. BCMoT should establish central repositories for technical, engineering, design, operation and climatic data necessary to conducting climate change vulnerability assessments for each highway segment contemplated for future vulnerability assessment studies.	N/A

8.5.2f Report on the other conclusions, trends, insights and limitations

The team originally conducted the risk assessment on 178 potential climate-infrastructure interactions. Based on the analysis the team identified that:

- 137, or 77% of the interactions had low or no material risk;
- 41, or 23% of the interactions had medium risk; and
- There were no interactions with high risk.

These risks are highlighted in the attached table.

This supports the conclusion that, overall, the infrastructure is relatively robust with respect to climate change.

Worksheet 5 Recommendations

DATE	March 7, 2011
PREPARED BY	Joel R. Nodelman (on behalf of BCMoTI Team)

Worksheet 5 Recommendations

Summary of Climate Change Risk Assessment Scores

Infrastructure Components	High Temperature	Low Temperature	Freeze/Thaw	Total Annual Rainfall	Extreme High Rainfall	Sustained Rainfall	Snow (Frequency)	Rain on Snow	Hail / Sleet	Rain on Frozen Ground	High Wind/ Downburst	Rapid Snow Melt	Snowmelt Driven Peak Flow Events (Spring Freshette)	Ice / Ice Jams	Ground Freezing
Above Ground															
Asphalt - Hot in Place	18	0	5												12
Asphalt - Seal Coat	6	0	5												12
Pavement Marking	0	0	5												
Shoulders (Including Gravel)	0		5		20	15									
Barriers					10										
Curb - Concrete			10		10										
Curb - Asphalt	0	0	5		10										
Luminaires										0	0				
Poles										0	2				
Signs - Sheeting											0				
Signs - Wood or metal bases										0	0				
Signage - Side Mounted - Over 3.2 m^2										0	4				
Signage - Overhead Guide Signs										0	4				
Overhead Changeable Message Signs - Weigh Scale										0	4				
Ditches			0	10	20	5		8				12			
Embankments/Cuts	0		5	10	20	15		8				16			
Natural Hillsides	0		5	10	10	10		8				12			
Engineered Stabilization Works															
Structures that Cross Streams - Bridges	24	6	15	10	15	10		8		3	0	4	15	6	
Structures that Cross Roads - Bridges	24	6	15		15	10		8		3	0				
Railways (Drainage Interaction)				10	10	10		8		0		8	10		
River Training Works - Rip Rap				10	15	10						4	15	6	
Retaining Walls - MSE Walls															
Asphalt Spillway and Associated Piping - Above Ground Elements	0		10	10	25	10		12		3		8			
Below Ground															
Pavement Structure			5	10		10									6
Catch Basins			10	5	25	10		12	0	6		8			
Roadway Drainage Appliances			10	5	25	10		12	0	6		8			
Sub-Drains		0	5	5	10	10		4							
Below Ground Third Party Utilities					10					0					
Above Ground Third Party Utilities										6					
Culverts < 3m		0	5	5	25	15		12	3			16	25	9	
Culverts ≥ 3m		0	5	5	15	10		4				4	20	9	
Piping/Culvert - Below Ground Elements.			5	5	20	10		12				8			
Miscellaneous															
Winter Maintenance		6	20		20		2	16		15	4	4		9	
Habitat Features															
Routine Maintenance	6	6	15		25	10				3	4	8			
Pavement Marking Repair							0								
Pavement / Curb/ Barrier / Sign Repair							2								

Appendix J

List of Workshop Participants

Workshop Attendees

First Name	Last Name	Position	Location
Jim	Barnes	Manager, Corporate Initiatives	BC MoT - Victoria
Gerd	Buerger	PCIC	PCIC - Victoria
Hugh	Donovan	Construction Services Engineer	Transportation - Edmonton
Bill	Eisbrenner	Manager, Geotechnical	BCMoT-Prince George
Doug	Elliot	District Technician	BCMoT - Victoria
Mike	Feduk	Sr. Hydrotechnical Engineer	BCMoT - Victoria
James	Hiebert	PCIC	PCIC - Victoria
Crystal	Lacher	Geotechnical Engineer	BCMoT - Victoria
Nini	Long	Manager Highway Design and Traffic Engineering	BCMoT-Prince George
Tom	Lupton	Road Area Manger	BCMoT - Vanderhoof
Ron	Mathieson	Sr. Bridge Design & Construction Engineer	BCMoT - Victoria
Ed	Miska	Section Head Traffic, Electrical, Highway Safety, Geometric Standards	BCMoT - Victoria
Joan	Nodelman	Consultant	Alberta
Joel	Nodelman	Consultant	Alberta
Daryl	Nolan	Environmental Services Manager	BCMoT - Prince George
Dirk	Nyland	Chief Engineer	BCMoT - Victoria
Ian	Pilkington	Chief, Geotechnical, Materials & Pavement Eng	BCMoT - Victoria
Darwin	Tyacke	Geometrics	BCMoT - Victoria
Gord	Wagner	Regional Manager, Engineering	BCMoT - Prince George