Analysis of a British Columbia resource road's vulnerability to climate change:

Tum Tum Forest Service Road PIEVC case study

Technical report no. 35 - June 2018

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301011965: Adapting roads to climate change

Technical Report no. 35

ABSTRACT

This report presents a case study of the vulnerability to climate change of infrastructure on the Tum Tum Forest Service Road using the Public Infrastructure Engineering Vulnerability Committee (PIEVC) protocol. This case study provided analysis of the risks and opportunities faced by the road, recommendations to mitigate the identified risks, and established a benchmark for future iterations of the process with resource roads.

ACKNOWLEDGEMENTS

This project was financially supported by Natural Resources Canada under the NRCan/CFS-FPInnovations contribution agreement and by the BC Ministry of Forests, Lands and Resource Operations & Rural Development under the FPInnovations – BC Agreement.

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COVER PHOTO

Photo from Tum Tum FSR overview presentation by Daryll Cairns of FLNRORD.

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1. EXECUTIVE SUMMARY

The management of resource roads is an important consideration for governments and industry across Canada. Resource roads support industrial operations, recreational activities and access for communities. The need to mitigate the impacts of climate change to resource roads and the requirement to identify and mainstream adaptation practices is of increasing importance. This need is of increased relevance in British Columbia where the varied and complex geography increases the impact of changes in climate patterns. In recognition of this, the B.C. government has developed a Climate Change Strategy mandate within the BC Ministry of Forests, Lands, and Natural Resource Operations & Rural Development (FLNRORD).

In support of both the broad climate change adaptation needs for resource roads in Canada, and to meet the specific objectives in B.C., FPInnovations partnered with FLNRORD to conduct a case study using the Public Infrastructure Engineering Vulnerability Committee (PIEVC) protocol to assess the vulnerability of a resource road to climate change. This case study analysed a 54 km long section of the Tum Tum Forest Service Road located approximately 125 kms northeast of Kamloops which has significant industrial and recreational use.

The climate modelling and forecasting determined that, in general for the area of the Tum Tum FSR, annual precipitation is forecasted to increase with less precipitation in the summer and greater amounts of precipitation in the form of rain in the winter. Warmer temperatures will occur in both winter and summer seasons with a shorter snow season forecasted.

The assessment team initiated determination of the severity and vulnerabilities for each of the 169 interactions between the selected types of infrastructure and climate parameters at a 2-day workshop. Due to time constraints, the analysis was completed by FPInnovations following the workshop in consultation with the assessment team. This report provides a series of recommendations as a result of the analysis. These recommendations include the need to streamline and focus the PIEVC process specifically for resource roads, capacity building actions by road managers and stakeholders, a review of emergency preparedness plans, the development of infrastructure inspection and inventory procedures, actions to review and improve the resiliency of stream crossing structures, and the need to further consider the impacts to forest management and road usage as a result of an earlier spring thaw.

This case study provides a benchmark for future iterations of the process, and provides meaningful analysis of the risks and opportunities faced by the Tum Tum FSR corridor.

2. INTRODUCTION

British Columbia has varied and complex geography and the predicted climate changes across the province are equally varied and complex. Climate change models for BC predict that by the 2050s the mean annual temperature will increase by 1° to 4° C. Along with the increased temperatures, it is anticipated there will be a marked contrast between wet and dry seasons, and more frequent extreme precipitation events and periods of hot dry weather. Regionally in BC it is expected that winters will be up to 20% wetter; and summers will be up to 15% drier in the south, and 10% wetter to 10% drier in the north. There also will be an increase in precipitation intensity.

As the effects of climate change begin to impact the natural resources that are integral to the prosperity of British Columbians, planning and implementation of climate change action, such as this analysis, will become common in the resource sector. As such, the Climate Change Strategy of the BC Ministry of Forests, Lands and Natural Resource Operations & Rural Development (FLNRORD) identified the need to integrate climate change adaptation into its core business, beginning with decision makers and staff viewing projects through a climate change mitigation reduction lens. Moving forward with the process, decision makers will be able to identify thresholds for climate change action and the economic consequences of reactionary versus precautionary action.

The management of resource roads and infrastructure continues to be an important activity for industries and governments across Canada. The planning, construction and maintenance of resource roads are required to support various industrial and resource management activities and are often the primary access for remote communities and public recreational experiences.

Given the significance that resource roads have to economic and social well-being, efforts are required to understand the implications of climate change in order to adapt roads and infrastructure to the impacts of climate change.

The adaptation of resource roads and infrastructure to climate change involves understanding risks and vulnerabilities, identifying infrastructure components where risks are greatest, and creating a strategy to ensure that the road and infrastructure components are made resilient.

In order to advance the understanding of the vulnerabilities of resource roads to climate change, and to identify measures to mitigate impacts, FPInnovations partnered with FLNRORD to conduct a risk and vulnerability assessment case study of the Tum Tum Forest Service Road (FSR) located north of Kamloops B.C.

Project objective

The principal objectives of this assessment were to:

- Evaluate the risks and vulnerabilities to climate change of the infrastructure on the Tum Tum FSR.
- Verify the PIEVC approach for application on resource roads.
- Derive general conclusions about the vulnerabilities and risks to climate change of resource road infrastructure.

Notice to reader

Assessing the moderately large number of possible climatic parameter and infrastructure element interactions (169 in total) was challenging to complete during the workshop. Further, considerable time was spent discussing how to assess (and whether to include) the vulnerability of environmental values within the resource road corridor. Some of the climatic parameters were not fully quantified in advance of the workshop, and participants found it difficult to relate return period data to the PIEVC probability of occurrence scale. For these reasons, the vulnerability assessments could not be completed during the workshop. Later, to complete the analysis, the assessment team refined the list of climatic parameters and infrastructure elements, FPInnovations resolved a method to link the climate data return periods to the PIEVC probability of occurrence scale, and FLNRORD provided the missing climatic parameter data. These tasks delayed the completion of the final report but provided valuable insights to support the successful completion of possible additional assessments.

Study scope and timing

The scope of the assessment included the current design, operation and management of the resource road infrastructure along the 54 km length of the Tum Tum FSR from KM 0 to KM 54.

The initial planning for the project began in December 2016 with final project reporting completed in April 2018. The assessment considered the climate change effects for two climate periods (1) baseline condition defined as the period of 2011-2040 and (2) future condition defined as the period of 2041-2070. The 2041-2070 period was chosen as the general lifespan and planning period of a resource road and its infrastructure components is approximately 30.

About the PIEVC protocol

A variety of management processes are available to assess the vulnerability of engineered structures to climate change, however, a method commonly used in Canada is the Public Infrastructure Engineering Vulnerability Committee (PIEVC) protocol (Engineers Canada 2016). The PIEVC protocol is a civil engineering tool used to assess the vulnerability of engineered structures to climate change. A variety of data are required to conduct a vulnerability analysis including infrastructure age, condition and inspection data, traffic volumes, geotechnical and terrain information, and extreme weather event data and its impact on infrastructure.

The PIEVC has created a five-step protocol to assess various infrastructure components, while focused on public and civil infrastructure; it also can be adapted to resource roads and infrastructure (figure 1). The PIEVC protocol reviews historic climate data, and projects the nature, severity, and probability of future events for a specific region. This information is then used to conduct a risk assessment of existing or planned infrastructure to determine if and what management response is required. This also provides managers and planners an opportunity to understand or establish the adaptive capacity of infrastructure, as determined by design, operations, maintenance, and policies.

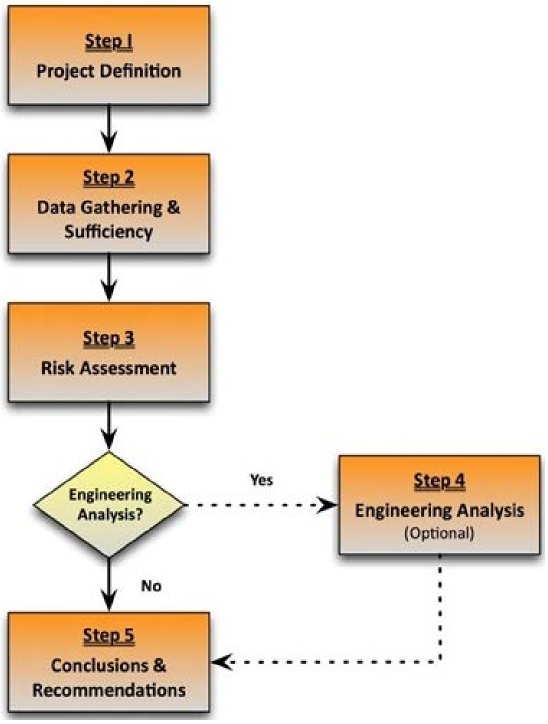


Figure 1. Stages in the PIEVC protocol. Reproduced from Engineers Canada 2016.

Step 1 - Defining the scope of the risk and vulnerability assessment is a crucial first step in ensuring that the analysis is effective, and that the conclusions and recommendations are relevant to the project objectives. The project definition includes identifying items such as the road segments to be studied, and stakeholders and road users to consult or consider.

Step 2 - During the data gathering and sufficiency step, it is important to consider which types of road and infrastructure components to gather data on (e.g., bridges, road surfacing, cut slopes), and which weather events historically occur in the area and directly influence the road and infrastructure components in strongly negative ways.

Step 3 - In the risk assessment step, climate parameters are selected which characterize the climatic changes of concern. Climatology predictions, with assumptions for various climate change scenarios, are run for the subject area and downscaled to provide localized predictions of the frequency and intensity of future weather events and climatic conditions on a local basis. The climate parameters of interest are then derived from these predictions. A high level risk assessment is made for each infrastructure element identifying which, and by how much, each climate parameter is likely to influence the performance of each type of road and infrastructure

Step 4 – If a type of infrastructure is found to be at high risk, an engineering analysis may be initiated. The engineering analysis step has various components, including verifying and refining the climatic predictions, and assessing load capacity vulnerability. Those familiar with the design of the infrastructure elements review the design assumptions, material properties, etc. to assess the anticipated changes in performance given the climate changes predicted. If design changes are warranted to ensure safety or reliability, then these are recommended.

Step 5 – The final step is the development of conclusions and recommendations in respect to possible operational or management actions required to upgrade the infrastructure. The overall resiliency and vulnerability of the infrastructure to climate change is described as well as any need to conduct additional analysis or further data gathering.

Project team

The assessment and advisory teams consisted of representatives from various industries and government departments to ensure that there was diversity in the knowledge, expertise and experience as related to the PIEVC process and the Tum Tum FSR. The members of the assessment team are listed in table 1.

Table 1. Assessment team members

Team Member	Position	Organization
Barry Trenholm	Engineering Group Leader	FLNRORD
Brian Chow	Chief Engineer	FLNRORD
Daryll Cairns	District Engineering Officer	FLNRORD
Dave Spittlehouse	Climatologist	FLNRORD
Allan Bradley	Associate Research Leader	FPInnovations
Mark Partington	Senior Researcher	FPInnovations
Mathieu Durand-Jézéquel	Researcher	FPInnovations

The assessment team engaged Joel and Joan Nodelman of Nodelcorp Consulting Inc. to facilitate the implementation of the PIEVC process and to lead the assessment team and advisory group through the vulnerability assessment during the workshop.

The advisory team participated in the vulnerability assessment workshop and provided local expertise and knowledge of the road and its surroundings, the road’s usage, and past and future desired performance levels. The members of the advisory team are listed in table 2.

Table 2. Advisory team members

Team Member	Position	Organization
Jessica Gunn	Area Forester	BC Timber Sales
Rowena Muglich	Engineering Technician	BC Timber Sales
Craig Shook	Senior Engineering Technician	FLNRORD
Gord Bower	Engineering Technician	FLNRORD
Leith McKenzie	TOR Climate Action Lead	FLNRORD
Martin Fennell	Senior Engineering Technical Specialist	FLNRORD
Paul Blueschke	Bridge Engineer	FLNRORD
Rita Winkler	Research Hydrologist	FLNRORD
Tim Giles	Regional Geomorphologist	FLNRORD
Craig Hewlett	Forest Supervisor	Gilbert Smith Forest Products Ltd.
Jim Miller-Tait	Exploration Manager	Imperial Metals Corp.
Mike Scott	Forestry Superintendent	Interfor
Wes Bieber	Consultant	Longfellows Nat. Res. Mgmt Solutions

3. STEP 1 – PROJECT DEFINITION

This section outlines the project parameters for each of the infrastructure and climate components.

General description of the infrastructure and site

The Tum Tum FSR is located approximately 125 kms northeast of Kamloops B.C. and originates north of Adams Lake and terminates at Tum Tum Lake Provincial Park. The scope of this assessment includes the length of road from KM 0 north of Adams Lake to KM 54 at the intersection of the Oliver Creek FSR (figure 2).

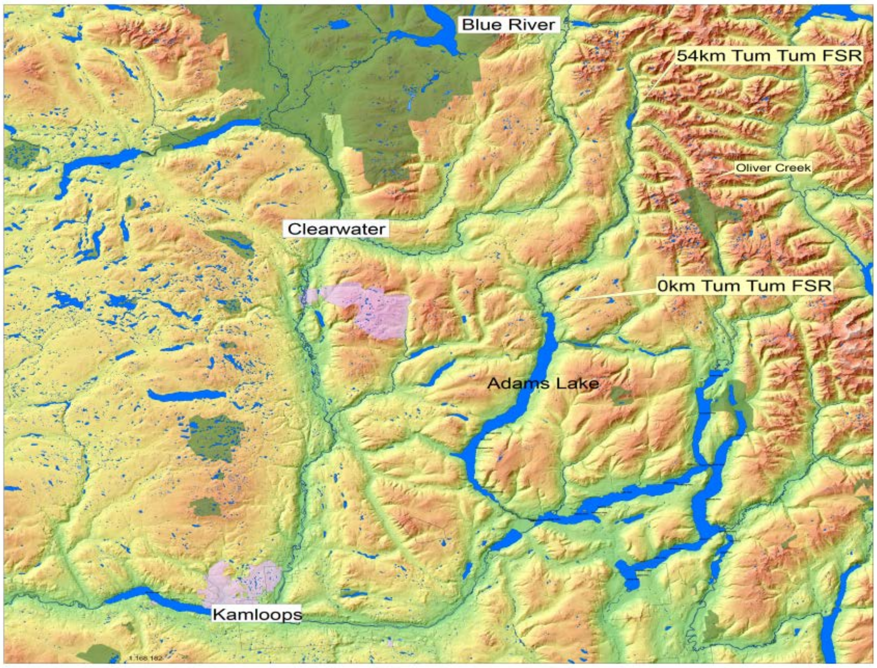


Figure 2. Map of the Tum Tum FSR. Image courtesy of Daryll Cairns.

The Tum Tum FSR is located beside the river within the Upper Adams River valley and much of its length lies in the Upper Adams River Provincial Park. The road terminates at Tum Tum Lake where there exist provincial park camp sites, private cabins and a recreation area. As a result of the recreational opportunities in the area there are significant levels of recreational traffic along the route. In addition, the road has significant industrial traffic supporting access to three industrial forest licensees as well as access to the proposed Ruddock Creek mine in the Oliver Creek valley. Because of the age of the road and the numerous licensees that have contributed to it, detailed inventory data on all infrastructures located along the road is not available; however there are ten bridges or major culverts that have been identified along the section of the Tum Tum FSR included in the assessment (figure 3).

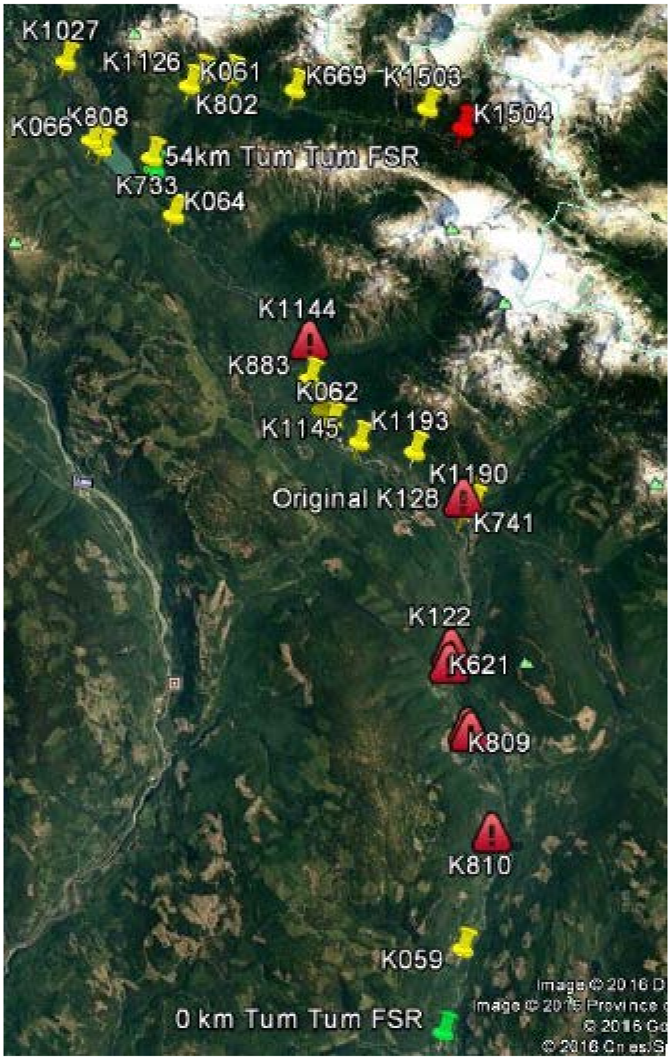


Figure 3. Major culverts and bridges (in yellow) located on the Tum Tum FSR. Image courtesy of Daryll Cairns.

Historic climate event observations

The Forestry Ministry file for the Tum Tum FSR was opened in 1974 but it is known that the road is much older with evidence of historic logging camps in the Upper Adams River valley. The first mention in the Ministry’s files of weather related damage is in April 1981 when flood damage necessitated repairs to four bridges and a 250 m-long section of road was repaired and widened at a total cost of $68 500.

In 1983, there was another mention of damage due to flash flooding with compensation to a forest licensee required for stranded vehicles due to a bridge washout.

In 1999 a spring rain event resulted in the washout of the Sunset Mammoth Bridge; the replacement bridge had to be sited at a new location.

More recently, in September 2015, a heavy rain storm damaged a 10 km-long section of the Tum Tum FSR. An estimated $500 000 in repairs was required, in addition to two new bridges to replace two culverts that had washed out (figures 4 - 6).

Figure 4. The road surface from KM 17.3 to 21 required repair following storm damage in September 2015. Photo courtesy of Daryll Cairns.

Figure 5. Culvert washout at KM 17 following storm damage in September 2015. Photo courtesy of Daryll Cairns.

Figure 6. Culvert washout at KM 17.3 following storm damage in September 2015. Photo courtesy of Daryll Cairns.

Climate parameter identification

The Tum Tum FSR is located in a valley where the surrounding terrain rises from 1 800 m on the Westside and 2 500 m on the eastside. Weather conditions at the road elevation are strongly influenced by the weather at those higher elevations as it is the source of water for streams that the road crosses.

Four weather stations are located adjacent to the Upper Adams River valley, and one station is located in the lower end of the valley (figure 7). Data from these weather stations were used in order to assess extreme precipitation, define temperature thresholds and evaluate the downscaled spatial data base. Daily river discharge for the Seymour River (located in an adjacent watershed) was obtained from the Water Survey of Canada.

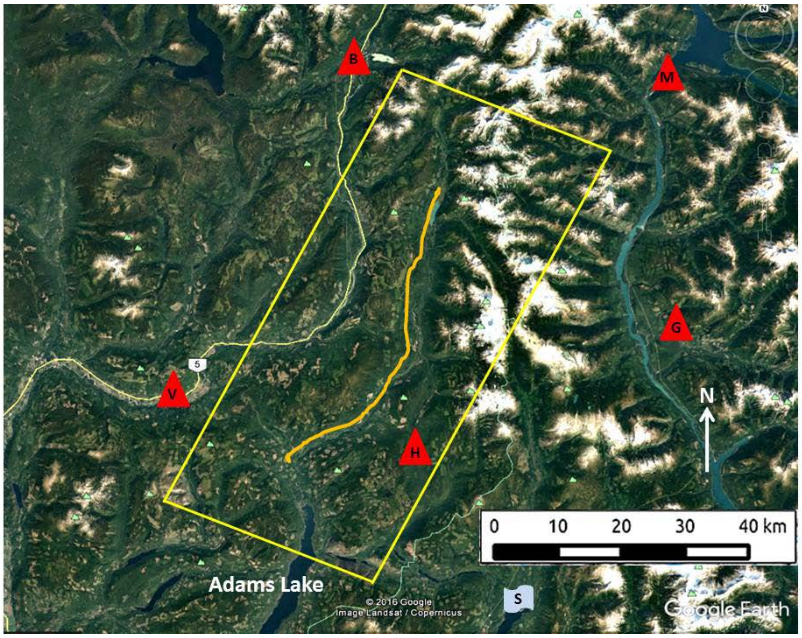


Figure 7. Tum Tum Forest Service Road (orange line), extent of the Upper Adams River Valley (yellow box), adjacent weather stations (red triangles) and Water Survey of Canada Seymour River hydrometric station (light blue flag) (Spittlehouse, 2017).

The twelve climate events that were included in the risk analysis are presented in table 3. The assessment team started with a list of climate events that were analyzed in previous PIEVC assessments conducted for British Columbia highways (BCMoTI 2010 and 2011), and the list was shortened to keep those that were determined to be most relevant to this assessment. High temperature, for example, is a climate event that was discussed within the assessment team, and it was decided that it did not need to be included in the analysis. The impact of an extreme high temperature on a resource road was considered minimal and was not included in the assessment.

Some of the events were removed from the initial list as they were unable to be modelled or could not be modelled effectively, such as fog and rain on frozen ground. However, local practitioners observed that ice jams in the river were seldom observed, but should be included in the analysis nonetheless because of their potential impact on the road.

Table 3. Climate parameters chosen for the assessment

Climate parameter	Elevation	Definition - threshold	Relevance to the infrastructure component
Drought conditions	Mid	Days with drought code from very high to severe	Wildfire hazard, increased runoff from hydrophobic soils, dusty conditions
Daily temperature variation	Road	Days with daily temperature variation > 25 °C	Relevance to bridges, thermal expansion/contraction
Freeze/thaw cycling	Mid	Days when $T_{max} > 0$ °C and $T_{min} < 0$ °C	Laminar ice build-up occurs on watercourses and ditches. Rock/ice fall onto road prism related to freeze/thaw
Cold spells	Mid	Periods with 7 days continuous maximum temperature < -5 °C	Water coming to the surface and freezing creates (1) ice build-up on rock faces resulting in rock and ice fall onto the road prism and (2) ice build-up in ditches, culverts and cross drains resulting in blockage
Spring thaw	Road	Thawing index; day of year CTI > 15 degree-days	Weak and thawing road conditions, no or spring load restricted (SLR) heavy traffic only
Extreme high rainfall in 24-hour period	High	1-day rainfall > 65 mm	High runoff, culverts and bridges damage or destruction, road surface damage or deterioration, safety
Sustained rainfall	High	3-day rainfall > 115 mm	High runoff, culverts and bridges damage or destruction, road surface damage or deterioration, safety
Antecedent rain followed by significant rain event	High	14-day antecedent rainfall > 80 mm followed by 1-day rainfall > 30 mm	High runoff and saturated soils, impacts to cut/fill slopes, landslides, culverts and bridges damage or destruction, road surface damage or deterioration, safety
Rapid snow melt (not with rain)	High	1-day snowmelt > 30 mm	Spring freshet conditions causing runoff and peak streamflow, culverts and bridges damage or destruction, road surface damage or deterioration, safety
Ice/ice jams	Road	Observed frequency of ice jammed in the river	Road blockage and/or flooding, uncontrolled erosion, unplanned closures
Snow frequency	Mid	Days with 10 cm of precipitation as snow ($T_{avg} < 1$ °C)	Snow plowing resulting in increased risk to damage of infrastructure
Snow accumulation	Mid	Days with a snow depth > 60 cm	Measure of how much snow accumulates on road edges due to snowfall and from snow plowing resulting in increased risk to damage to signs and barriers, snow on hills above road

The climate parameters are related to a weather event that can be projected by a global climate model (GCM), except for the ice/ice jams for the reason previously mentioned. The assessment team attempted to evaluate the impacts of a wildfire on its own, but the idea was rejected as it was not in itself a climate event. The decision was made that it would be included under the drought conditions event which is based on the drought code, a numeric rating of the dryness of deep organic soil horizons. Drought code is a component of the Canadian Forest Fire Weather Index System. It is evaluated using the factors of temperature and rain with a daily rating ≥ 300 indicating a very high to severe drought.

Spring thaw was considered in the assessment and is not in itself a climate event but it is modelled using the cumulative thawing index (CTI). CTI is used as a threshold to initiate spring load restrictions (SLR) in various jurisdictions in North America (Spittlehouse, 2017). A typical CTI value of 15 degree-days was chosen for use in this assessment which provides a result that indicates the day of the year when the SLR period would begin.

The other climate parameters are clearly defined and have specific thresholds. For events that have a return period of a few years, the threshold weather conditions were defined to be higher than historical levels. As for events that occur annually (snow accumulation for instance), the threshold value was more arbitrary. Some climate events, such as freeze/thaw cycling, have a fixed definition based on the nature of the event.

In addition, each of the climate parameters was assigned an elevation based on their evaluated impact. For instance, temperature variations are relevant at the road level due to their direct influence on structures such as bridges, whereas precipitation and snow melt at higher elevations affect timing of hydrologic events which occur at the road. Changes in weather events (extreme temperature and precipitation) with time may be similar across the watershed, but their magnitude varies with elevation. Return periods for extreme rain events at higher elevations are typically reduced. Consequently, spatial averages of weather events were assigned according to their respective elevation:

- Road elevation (~500 m);
- Areas above the road (~800 m), and;
- High elevation (~1 900 m).

Site visit

A field review of the Tum Tum FSR was not conducted prior to the assessment workshop due to the presence of heavy snow cover on the road. The assessment team determined that a site visit was not necessary for the successful assignment of vulnerability and severity in order to determine risk for this assessment.

The extensive experience of the assessment and advisory teams regarding historical road performance challenges as well as forecasted road usage and management was determined to be sufficient to ensure accurate assignment of risk during the assessment process.

4. STEP 2 – DATA GATHERING AND SUFFICIENCY

The assessment team started with a list of 45 infrastructure components and 17 climate events. Some of the items were removed due to their irrelevance, whereas others were added to properly evaluate the infrastructure components and climate interactions that are specific to a resource road.

Identification of applicable infrastructure components

The assessment team considered a wide range of infrastructure components throughout the process before determining the final list.

The infrastructure components and operational considerations that were considered in the risk analysis are presented in table 4 and include a description of each infrastructure component impact of failure to aid in understanding the function of each component and how the road may be affected in case of failure.

The list of infrastructure components was shortened to the fifteen most relevant items for the TumTum FSR as determined by the assessment team. The original list included third party utilities and environmental features, but it was decided not to include these components as it was out of the scope of this assessment. Other above ground components such as barriers and signage were not included due to their low priority for management and the minimal weather impacts these components have experienced.

Infrastructure components were divided into four categories:

- Road prism features including embankments, side slopes, cross drains, ditches, and catch basins.
- Stream crossings, including bridges and other major structures (e.g., culverts and arches), and minor structures (i.e., other culverts).
- Upslope/downslope areas beyond the road prism.
- Operational considerations including access, maintenance, and personnel. These capture road user safety and the maintenance responses when extreme weather events occur.

Table 4. List of infrastructure components used in the assessment

Infrastructure components and operational considerations	Description of infrastructure components	Impact of failure
Road prism features		
Road surface	Running surface and road shoulders	Road functionality, maintenance, safety
Cut fill and slope	Constructed slopes beside road	Road functionality, maintenance, drainage, and can propagate to areas uphill or downhill
Ditches and cross ditches	Water drainage ditches to either side of road shoulders	Road functionality, maintenance, drainage, and downhill slope stability and streams
Catch basins	Basin constructed in ditch to direct water into cross drain or cross ditch	Road functionality, maintenance, drainage, and downhill slope stability and streams
Cross drains	Culverts in road to drain ditch water to opposite side of road	Road functionality, maintenance, drainage, and downhill slope stability and streams
Stream crossings		
Major culverts > 2.0 m	Culvert diameter of 2.0 m or larger	Flooding, road prism washouts, structure loss, road closure, disruption of stream habitat
Other culverts < 2.0 m	Culvert diameter less than 2.0 m	Flooding, road prism washouts, structure loss, road closure, disruption of stream habitat
Bridges	All bridges	Road approach washouts, structure loss, road closure, disruption of stream habitat
Upslope/downslope beyond road prism		
Managed (Upper Adams River Provincial Park)	Right-of-way, harvest blocks, managed park	Ditch and culvert blockage, road closure, debris on road, diverted drainage
Unmanaged	Right-of-way, conservation areas, non-forestry areas	Ditch and culvert blockage, road closure, debris on road, diverted drainage
Operational considerations		
Commercial and recreational access	All industrial traffic, light recreational vehicles	Access restricted, road user safety compromised
Emergency response	Emergency response vehicles, ground transport	Access restricted, road user safety compromised, health risk
Winter maintenance	Plowing, grading, sanding/salting, culvert de-icing	Winter maintenance response (cost, effort) increased
Summer maintenance	Grading, dust abatement, ditch cleaning	Summer maintenance response (cost, effort) increased
Personnel	Light and maintenance vehicles travel	Access restricted, road user safety compromised

Identification of applicable climate information

The assessment team engaged the Pacific Climate and Impacts Consortium (PCIC) to develop the climatic data projections for the study area. A comprehensive analysis and climate variable development was then performed by Dave Spittlehouse, FLNRORD climatologist, based on the climatic data projections (Spittlehouse, 2017).

A polygon the 54 km length of the road by 30 km wide centred on the road was used by PCIC to define the area of interest for the spatial climate summaries.

With those data, different climate change scenarios were selected in order to provide a wide spread in projected future climate for calculating specific variables for the PIEVC protocol analysis.

An example of climate variation within the watershed is shown on figure 8. Such a variation is mainly due to the change in elevation across the valley rather than a north-south gradient. Spatial variability entails a challenge for the analysis as data have to be relevant to the road infrastructure.

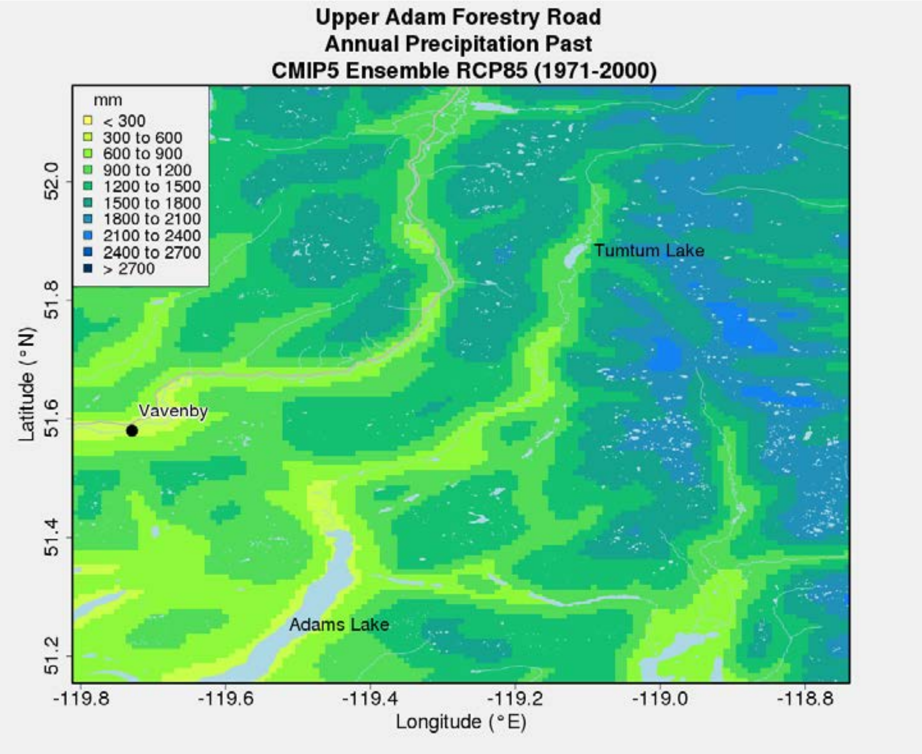


Figure 8. Mean annual precipitation for the 1971-2000 periods (Spittlehouse, 2017).

In summary the climate modelling and analysis highlighted the following results (Spittlehouse 2017):

- Warming is projected to occur in all seasons with temperatures increasing by 2-4°C by the 2041-2070 period.
- Summers are projected to be drier and winters wetter.
- The 20-year return period annual maximum 1-day and 3-day precipitation are projected to increase by 20%-50% by the 2071-2100 period.
- Snow packs will decrease at lower elevations, but may show an increase at the higher elevations.
- A warming winter means that there will be an increase in winter streamflow, an earlier melt season and the potential for increased size of snow-melt driven peak flows.
- Warmer and drier summers will increase fire risk and maximum temperatures will reach the mid to high 30°C at the road level.

Projected data were calibrated using data from the 1971-2000 period. With a downscaled global climate model (GCM) using daily weather data from the past, data for three, distinct, 30-year period were projected:

- 2011-2040 period;
- 2041-2070 period, and;
- 2071-2100 period.

Since the risk assessment was conducted in 2017, data from the 2011-2040 period were established as the baseline conditions. Future conditions were based on data from the 2041-2070 period. This means that both baseline and future periods rely on modeled data; the baseline period is not based on actual weather data that were recorded recent years. This distinction is important as it means that the baseline data already show the influence of climate change, compared to the previous period. Road users and practitioners already observed effects from climate change in recent decades, and this analysis reflects that.

Different climate parameters were analyzed using modeled temperature and precipitation data, but only those that are relevant to the road infrastructure were kept in the risk analysis (table 5).

Table 5. Climate parameters used for baseline and future periods

Climate Component	Definition	Baseline (2011-2040)		Future (2041-2070)		Reliability[c]
		Days per year[a]	Return period[b]	Days per year[a]	Return period[b]	
Drought conditions	Days with drought code from very high to severe @ mid elevation	8 (0 to 22)		15 (0 to 44)		H
Daily temperature variation	Days with daily temperature variation > 25 °C @ road elevation	1 (0 to 6)		2 (0 to 9)		H
Freeze/thaw	Days when $T_{max} > 0$ °C and $T_{min} < 0$ °C @ mid elevation	103 ± 20		83 ± 25		H
Cold spells	Periods with 7 days continuous maximum temperature < -5 ° C @ mid elevation	2 (0 to 10)		2 (0 to 14)		H
Extreme high rainfall in 24-hour period	1-day rainfall > 65 mm @ high elevation		5		3	M
Sustained rainfall	3-day rainfall > 115 mm @ high elevation		10		5	M
Antecedent rain followed by significant rain event	14-day antecedent rainfall > 80 mm followed by 1-day rainfall > 30 mm @ high elevation	4 (1 to 10)		4 (1 to 11)		L
Snow frequency	Days with > 10 cm of precipitation as snow ($T_{avg} < 1$ °C) @ mid elevation	4 (1 to 11)		4 (0 to 10)		M
Snow accumulation	Days with a snow depth > 60 cm @ mid elevation	55 (0 to 120)		35 (0 to 105)		M
Rapid snow melt (not with rain)	1-day snow melt > 30 mm @ high elevation	7 (1 to 13)		7 (1 to 14)		M
Ice / ice jams	Observed frequency of ice jammed in the river	n.a.	n.a.	n.a.	n.a.	n.a.
Spring thaw	Thawing index; day of year CTI > 15 degree-days @ road elevation	April 20th ± 15		April 10th ± 20		M

[a] Average (10th percentile to 90th percentile)

[b] Return period values are in years

[c] Reliability of projections are either High, Medium or Low

5. STEP 3 – RISK ASSESSMENT

The assessment and advisory teams met on March 14th and 15th 2017 in Kamloops B.C. to review the climate modelling, determine the applicable infrastructure components and to assign severity and vulnerability scores as necessary to perform the risk assessment. This working meeting was led and facilitated by Joel and Joan Nodelman of Nodelcorp Consulting who were engaged by FPInnovations to facilitate the working meeting and to provide direction and advisement throughout the process of the PIEVC protocol application.

At the workshop the assessment and advisory teams consumed considerable time reviewing infrastructure components and climate parameters that were most relevant for this case study. As a result, FPInnovations reviewed the probability and severity information developed at the workshop and for those scores that were not completed; FPInnovations determined the relevant scores in consultation with the assessment team following the workshop.

Risk assessment spreadsheet

The assessment team used a spreadsheet to assess risks and vulnerabilities and to identify the interactions between infrastructure components and climatic events. The content of the spreadsheet is presented in the following sections.

Spreadsheet format

The spreadsheet is structured as a matrix in which the rows are infrastructure components and columns are the climate parameters. To assist the team to identify the response characteristics of each infrastructure component, a performance response consideration is used. The probability, severity and risk scores appear in the risk analysis field (figure 9).

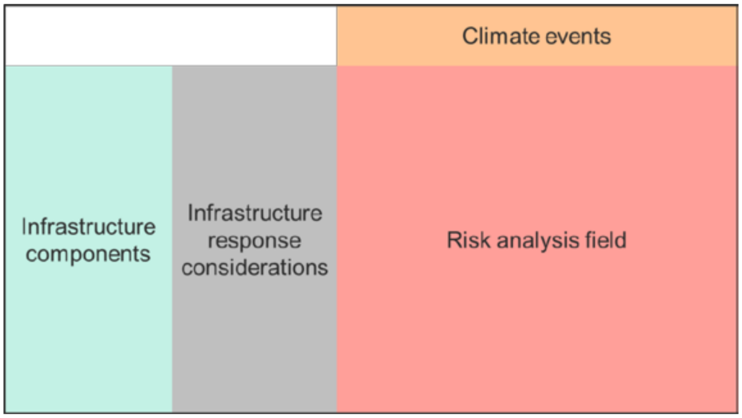
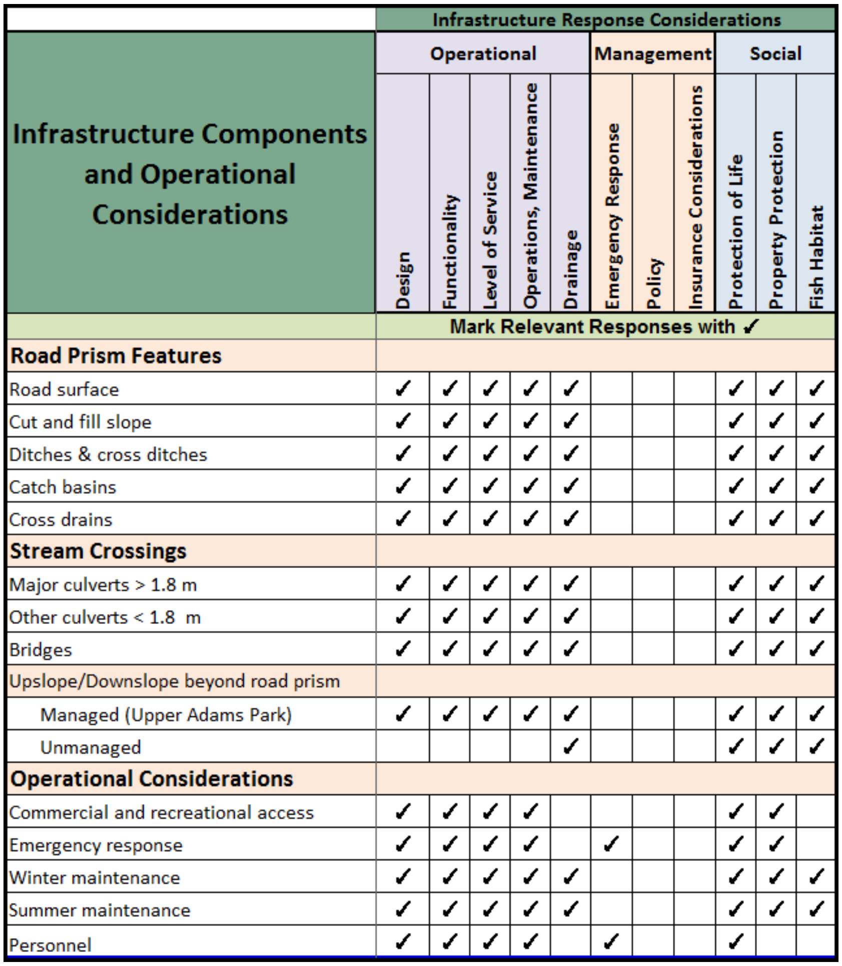


Figure 9. Schematic of spreadsheet used in the risk assessment.

Performance response considerations

Once the infrastructure components and climate events lists are completed, the assessment team refers to the performance response considerations of each component of the infrastructure. This ensures that each component is well understood and its contributions to the risk analysis recognized. The response considerations are part of a screening process and the team can refer to this when assigning severity scores in the risk analysis field. If an infrastructure component shows no performance response, it means that it should not be assessed within the framework of the protocol. The value in this work is to better understand how the components may respond to extreme events. The final infrastructure response results are shown in figure 10.



	Infrastructure Response Considerations											
	Operational					Management			Social			
Infrastructure Components and Operational Considerations	Design	Functionality	Level of Service	Operations, Maintenance	Drainage	Emergency Response	Policy	Insurance Considerations	Protection of Life	Property Protection	Fish Habitat
	Mark Relevant Responses with ✓											
Road Prism Features												
Road surface	✓	✓	✓	✓	✓				✓	✓	✓
Cut and fill slope	✓	✓	✓	✓	✓				✓	✓	✓
Ditches & cross ditches	✓	✓	✓	✓	✓				✓	✓	✓
Catch basins	✓	✓	✓	✓	✓				✓	✓	✓
Cross drains	✓	✓	✓	✓	✓				✓	✓	✓
Stream Crossings											
Major culverts > 1.8 m	✓	✓	✓	✓	✓				✓	✓	✓
Other culverts < 1.8 m	✓	✓	✓	✓	✓				✓	✓	✓
Bridges	✓	✓	✓	✓	✓				✓	✓	✓
Upslope/Downslope beyond road prism											
Managed (Upper Adams Park)	✓	✓	✓	✓	✓				✓	✓	✓
Unmanaged					✓				✓	✓	✓
Operational Considerations											
Commercial and recreational access	✓	✓	✓	✓					✓	✓	
Emergency response	✓	✓	✓	✓		✓			✓	✓	
Winter maintenance	✓	✓	✓	✓	✓				✓	✓	✓
Summer maintenance	✓	✓	✓	✓	✓				✓	✓	✓
Personnel	✓	✓	✓	✓		✓			✓		

Figure 10. Performance response considerations.

Yes/No analysis

Once the performance response considerations analysis is completed, the screening process continued with the yes/no analysis. At this stage, the assessment team evaluated whether it is believed the infrastructure component interacts with the climate event. For instance, a buried structure may not be affected by an extreme high temperature; in this case, this interaction would not be assessed. The purpose of this analysis is to streamline the assessment process and to avoid assigning probability and severity scores to an interaction that will not affect that infrastructure.

In this study, it was found that every road prism feature, stream crossing or slope beyond road prism was exposed to climate events. The only occurrences where some interactions were not assessed were when a seasonal climate event and a seasonal operational component occurred, such as summer or winter maintenance. Out of a total of 180 possible interactions (15 infrastructure components and 12 climate events), 11 interactions were withdrawn from the yes/no analysis, for a total of 169 interactions to assess.

Probability scores

In the risk assessment, the practitioner must assign a probability value to indicate if a certain weather event will occur. The team had access to climatic data using climate modelling data downscaled to the region around the Tum Tum FSR. It was possible using this model to assess the probability of an event occurring at the current and forecasted periods. For certain climate events, the probability was reported in terms of a return period (i.e., 5 or 10 years); for events that occurred every year, such as freeze/thaw cycling, the probability was reported as the number of days per year. For the ice/ice jams event, it was solely based on observations using practitioners’ experience with the Tum Tum FSR.

To assess probability, the protocol uses a standardized scale of scores from 0 to 7, with 0 representing that the event will not occur and 7 representing that the event will occur. The team had the option to choose between two methods within the PIEVC protocol to assign probability:

- Method A, which is more qualitative, and;
- Method B, which uses an annual probability of an event happening.

It is preferable to use method A if the assessment team does not have access to good quality data, and relies mostly on road users’ experience to assess probabilities.

However, method B was chosen because outputs from the climate forecasting provided the required data. The two methods are summarized in table 6.

Table 6. PIEVC protocol definitions of probability

Score	Probability	
	Method A	Method B
0	Negligible Not applicable	**< 0.1 %** **< 1 in 1,000**
1	Highly unlikely Improbable	**1 %** **1 in 100**
2	Remotely possible	**5 %** **1 in 20**
3	Possible Occasional	**10 %** **1 in 10**
4	Somewhat likely Normal	**20 %** **1 in 5**
5	Likely Frequent	**40 %** **1 in 2.5**
6	Probable Very frequent	**70 %** **1 in 1.4**
7	Highly probable	**> 99 %**

Probability scores are determined for the baseline period, and for any future predictions. In this study the future prediction was for the period of 2041 to 2070 because this provided the most meaningful info about infrastructure service life.

In the climate reporting, depending on the climatic event, probabilities may be given in a number of occurrences (days) per year, while others are given in a return period (years). When probabilities are given in terms of a return period, the probability scores are assigned according to the PIEVC standard scale using method B. When weather events occur many times throughout the year, probability scores of 5, 6 or 7 are given, depending on the number of days. For example, a score of 6 was given to drought conditions occurring 8 to 15 days per year, whereas the highest score of 7 was given to freeze/thaw when around 100 cycles per year occurred. As a result a small change in the probability that a climatic event will occur is not reflected in the probability scores. For example, even if the number of days of a drought condition doubles in the next 30 years, the probability score of 6 remains the same. The freeze/thaw cycle will be observed, on average 20 times less on the Tum Tum FSR by 2041, but the 83 cycles is still frequent enough that the probability score remains the same. The results of the probabilities, as determined by the assessment team, are shown in table 7.

Table 7. Climate parameters and their assigned probabilities for current and future periods

Climate Component	Definition	Baseline (2011-2040)	Future (2041-2070)
		Score	Score
Drought conditions	Days with drought code from very high to severe @ mid elevation	6	6
Daily temperature variation	Days with daily temperature variation > 25 °C @ road elevation	5	5
Freeze/thaw	Days when T_{max} > 0 °C and T_{min} < 0 °C @ mid elevation	7	7
Cold spells	Periods with 7 days continuous maximum temperature < -5 ° C @ mid elevation	5	5
Extreme high rainfall in 24-hour period	1-day rainfall > 65 mm @ high elevation	4	5
Sustained rainfall	3-day rainfall > 115 mm @ high elevation	3	4
Antecedent rain followed by significant rain event	14-day antecedent rainfall > 80 mm followed by 1-day rainfall > 30 mm @ high elevation	6	6
Snow frequency	Days with > 10 cm of precipitation as snow (T_{avg} < 1 °C) @ mid elevation	5	5
Snow accumulation	Days with a snow depth > 60 cm @ mid elevation	7	6
Rapid snow melt (not with rain)	1-day snow melt > 30 mm @ high elevation	6	6
Ice / ice jams	Observed frequency of ice jammed in the river	n.a.	n.a.
Spring thaw	Thawing index; day of year CTI > 15 degree-days @ road elevation	7	7

Severity scores

In order to assess risk, the second step is to assess the consequences of a climate event happening on the infrastructure components. Unlike probability, severity scores are not based on specific models; practitioners must rely on their experience, expertise and knowledge to ensure a reliable severity rating on each of the infrastructure components. Severity scores provide an indication of how the infrastructure serviceability, capacity, function, and service life are impacted by a climate parameter and how costly and problematic the management response(s) are.

The same scale of 0 to 7 that was used in the probability rating also is used for severity scores. A score of 0 indicates no negative consequences, and a score of 7 indicates that the infrastructure will fail, should the climate event occur. Once again, two methods are available: method D and method E as shown on table 8.

Table 8. PIEVC definitions of severity

Score	Severity of consequences and effects	
	Method D	Method E
0	No effect	Negligible Not applicable
1	Measurable	Very Low Some measurable change
2	Minor	Low Slight loss of serviceability
3	Moderate	Moderate loss of serviceability
4	Major	Major loss of serviceability Some loss of capacity
5	Serious	Loss of capacity Some loss of function
6	Hazardous	Major Loss of function
7	Catastrophic	Extreme Loss of asset

In this assessment, method E was used because it was judged by the assessment team to be more accurate, robust and rigorous when rating the different infrastructure components. Each of the 169 interactions was assigned a severity score; scores were based on the assessment team's experience and professional judgment.

Risk scores

Once the probability and severity scores are obtained, it is possible to determine the risk of each climate event and infrastructure component interaction. The PIEVC protocol defines risk as follows:

$$R = P * S$$

where risk (R) is the product of the probability (P) of an event and the severity (S) of that event, should it occur. Nodelman (2017) mentions that "risk is an estimate of the seriousness of a vulnerability response of an asset to an anticipated weather event". The result of the product of the probability score and the severity score produces a risk score, which can range from 0 (no risk) to 49 (highest risk possible).

The PIEVC protocol provides direction for the application of risk tolerance thresholds of high, high-medium, low-medium and low. The assessment team adopted this framework for application in this study (table 9).

Table 9. Risk tolerance thresholds and color codes

Threshold	Risk range	Response
Low	< 13	No action required
Low-Medium	13 - 25	Remedial actions may be required
High-Medium	26 - 36	Remedial actions may be required
High	>36	Immediate action required

The risk thresholds can be adapted to each project; this is up to the infrastructure owner to decide what the risk tolerance is. In this study the assessment team adopted both the low-medium and the high-medium thresholds as a means to highlight changes in risk from the baseline and future climate periods.

Special cases may arise where a risk scores equals 7 and this may require special attention in two cases:

1. If the probability is very low ($P = 1$) and the severity is very high ($S = 7$), the interaction may be potentially devastating and may result in a loss of asset. Even if the event is unlikely to occur, this case warrants special attention by the practitioner. It may be decided that it does not require further action, or that it needs to be addressed with an emergency plan, for example.
2. If the probability is very high ($P = 7$) and the severity is very low ($S = 1$), the interaction may indicate that the infrastructure component will experience increased weathering over time, even though the weather event is not extreme. This could increase overall maintenance cost, so a special attention should be given to those cases as well.

Risk score analysis

A risk score analysis as determined by the assessment team is presented in table 10 for the baseline period, which represent the current risk (i.e., from 2011 to 2040), and for the forecasted climate condition in the period from 2041 to 2070.

Table 10. Summary of risk scores for baseline (B = 2011 to 2040) and future (F = 2041 to 2070) periods

Infrastructure components	Drought		Daily temp. variation		Freeze/ thaw		Cold spells		Spring thaw		Extreme rainfall		Sustained rainfall		Ante. rain		Rapid snow melt		Ice / ice jams		Snow freq.		Snow accum.	
Baseline / Future	B	F	B	F	B	F	B	F	B	F	B	F	B	F	B	F	B	F	B	F	B	F	B	F
Road prism																								
Road surface	12	12	5	5	7	7	5	5	28	28	12	15	9	12	18	18	6	6	6	6	10	10	14	12
Cut fill and slope	6	6	5	5	7	7	5	5	7	7	12	15	9	12	18	18	6	6	0	0	10	10	14	12
Ditches	0	0	5	5	21	21	5	5	7	7	12	15	9	12	18	18	12	12	4	4	5	5	7	6
Catch basins	0	0	5	5	14	14	15	15	7	7	8	10	6	8	12	12	12	12	0	0	5	5	7	6
Cross drains	0	0	0	0	14	14	15	15	7	7	20	25	15	20	30	30	12	12	6	6	0	0	N	N
Stream crossings																								
Major culverts	0	0	0	0	21	21	5	5	7	7	16	20	12	16	24	24	12	12	0	0	0	0	N	N
Other culverts	0	0	0	0	21	21	15	15	7	7	20	25	15	20	30	30	18	18	0	0	0	0	N	N
Bridges	6	6	5	5	21	21	5	5	7	7	24	30	18	24	36	36	18	18	0	0	15	15	21	18
Upslope/downslope beyond road prism																								
Managed	12	12	0	0	7	7	5	5	7	7	12	15	9	12	18	18	6	6	0	0	0	0	7	6
Unmanaged	12	12	0	0	7	7	5	5	7	7	8	10	6	8	12	12	6	6	0	0	0	0	7	6
Operational considerations																								
Commercial access	24	24	0	0	14	14	10	10	28	28	20	25	15	20	30	30	6	6	6	6	5	5	7	6
Emergency response	18	18	0	0	14	14	5	5	7	7	20	25	15	20	30	30	6	6	6	6	5	5	7	6
Winter maintenance	N	N	0	0	21	21	15	15	7	7	N	N	N	N	N	N	12	12	6	6	10	10	14	12
Summer maintenance	12	12	0	0	N	N	N	N	N	N	12	15	9	12	18	18	N	N	N	N	N	N	N	N
Personnel	18	18	0	0	14	14	0	0	0	0	12	15	9	12	18	18	6	6	6	6	5	5	7	6

1. A risk score of “N” indicates that the infrastructure component was not assessed for risk to the corresponding climate factor.

Discussion

The assessment team evaluated risk on 169 potential climate and infrastructure interactions for each of the baseline and future periods. Based on the analysis performed it was identified that:

- 71% of the interactions in the baseline period and 69% in the future periods were considered low risk.
- 25% of the interactions in the baseline period and 24% in the future periods were considered low-medium risk.
- Only 4% of the interactions in the baseline period and 7% in the future periods were considered high-medium risk.
- None of the interactions were considered high risk for either the baseline or future periods.

Baseline (2011-2040) period

The assessment team determined that the highest risk scores were associated with the weather parameter antecedent rain followed by a significant rain event. Bridges, small culverts and cross drains were found to have a high-medium risk while operational considerations such as commercial and recreational access and emergency response also showed a high-medium risk. Additional rain events, extreme rainfall and sustained rainfall show medium risks for bridges, small culverts and cross drains because the probability that those rain events occurring is reduced. The three climate parameters related to rain were assigned the same severity scores because the team judged that the consequences would be the same. As a result the changes in risk scores for each of the rain events were solely attributable to changes in probability scores.

Spring thaw is the only other climate parameter that showed high-medium risk scores. Other climate parameters that have an impact on infrastructure include freeze/thaw cycling, rapid snowmelt and snow accumulation which show a medium risk for most of the infrastructure components, but the highest risk scores for those climate events were for stream crossings.

Road surface and commercial and recreational access had the highest risks, whereas all other infrastructure components were in the low risk category.

In the baseline period, no interactions had a risk score over 36, meaning that none of the infrastructure components were at “high risk” to any of the climate events. It was mentioned earlier that a high risk interaction usually demands immediate response, while medium risk interactions may or may not require remedial action. In the case of the Tum Tum FSR, the highest risk in the baseline period was for culverts and bridges experiencing heavy rain events. As mentioned in Step 1 – Project definition, significant rain events did occur in the two years prior to this assessment and this caused some culverts and bridges to fail. The risk analysis for the baseline period appears to be reasonable because the infrastructure components that are found to be at higher risk were the ones that recently had failed (although it was not possible to determine what type of rain event caused the flash flood in September 2015).

It may not seem logical that an extreme event that occurred recently is not considered to be high risk according to the PIEVC standard scale. This may be because such events occur so rarely that they are not considered to be a high risk (severity is high, but probability is too low to put it in the high risk category). Another reason to explain this is the fact that the threshold of 36 can be changed by the infrastructure owner in order to reflect the tolerance to risk. This threshold can be lowered if it is felt that risk scores obtained in the spreadsheet are too low to reflect what has already been observed in the current time period. It is up to the infrastructure owner to decide if the interactions with the highest risks need to be immediately addressed.

Future (2041-2070) period

The assessment team determined that the highest risk score was for the antecedent rain followed by a significant rain event. Extreme rainfall events show high-medium risks when impacting stream crossing infrastructure components and some operational considerations (commercial and recreational access, emergency response). Risk scores for sustained rainfall event are somewhat increased but stay in the same medium risk category, in general.

The risk with snow accumulation interactions was low, in general, because this event results in low severity responses for infrastructure components.

For all other weather events, the risk did not change when compared to the baseline period.

Comparison between baseline and future periods

It is important to highlight that the difference in risk scores between future and baseline periods is created by the change in the probability score. For instance, a 1 day-long rainfall with 65 mm of rain will have the same consequences in the future as now, which means severity scores do not change with time. The risk analysis for the future is rather simple: the assessment team uses the baseline period spreadsheet, and changes the probability scores according to the projected climatology report for the Tum Tum FSR (Spittlehouse, 2017).

Some potential benefits to the management of the Tum Tum FSR were indicated by the vulnerability analysis. The risk associated with snow accumulation will decrease, which could result in savings in terms of winter maintenance cost and bridge repairs. If less snow is expected in the future, less snow plowing would be necessary and less plow damage to bridge guard rails may result, also.

Another interesting outcome is that spring thaw will happen on average 10 days earlier in the future as compared to the baseline period. This means that the period of winter operations could be reduced, which will impact planning and management of forest operations. Notably, resource extraction hauling (logs and mining) could be restricted earlier in the year as well.

Risk is not predicted to change for most of the infrastructure and climate interactions in the future. In general, extreme rain events may occur more frequently and the snow cover in the winter may be reduced but overall risk levels are not predicted to not increase dramatically.

6. STEP 4 – ENGINEERING ANALYSIS

The engineering analysis step is an optional component of the PIEVC protocol and has various possible components, including refining the climatic predictions, and assessing load capacity vulnerability. Those familiar with the design of the infrastructure elements can review the design assumptions, material properties, etc. to assess the anticipated changes in performance given the climate changes predicted. If design changes are warranted to ensure safety or reliability, then these are recommended.

The assessment team determined that considering the scope and objectives of the case study and the information available it was not necessary to perform an engineering analysis of the infrastructure response to climate change on the Tum Tum FSR.

7. STEP 5 – RECOMMENDATIONS AND CONCLUSIONS

Limitations

Detailed maintenance, inventory and performance data concerning the Tum Tum FSR were not available for consideration by the assessment and advisory teams. Historical data relied on road user commentary because a detailed database of maintenance activities, costs, and changes in road usage and management were unavailable.

The lack of specific road data and accurate weather data for the region encompassing the Tum Tum FSR guided the assessment team to create a baseline risk analysis to be used in the case study based on modelled climate conditions rather than current and historical data and road performance.

The ice jam climate parameter was unable to be modelled and, instead on the experience and road performance estimates, as determined by the assessment and advisory teams.

Recommendations

The assessment team developed general recommendations concerning the implementation of the PIEVC protocol on resource roads as well as specific recommendations for the Tum Tum FSR arising from the results of the risk and vulnerability assessment.

General

The PIEVC process provided a formal, systematic, and comprehensive approach to the assessment the vulnerabilities of the Tum Tum FSR's infrastructure to climate related impacts. The process effectively compiled local knowledge and technical expertise about extreme weather impacts and extended these into the future using climatology prediction methods. More specific recommendations include:

1. It is recommended that the PIEVC process applied to resource roads be streamlined so that the process focuses on a pre-sorted set of resource road infrastructure and key climatic parameters. This would allow the workshop participants to gain better efficiency and effectiveness of their time and would allow the discussions to focus on assigning vulnerability and severity ratings and understanding of the resulting risk scores. In this assessment, the assessment and advisory teams spent considerable time discussing the value of the various infrastructure components and climate parameters that should be considered. If these parameters had been agreed upon in advance, the discussions at the workshop could have remained more focused.
2. Ensure that the relationships between the potential infrastructure components and climate parameters are well defined. Not all climate parameters and infrastructure components interact to such a degree that necessitates assigning a risk score. Understanding and identifying the relationships would aid the assessment and advisory teams in recognizing the most critical and vulnerable impacts to infrastructure of climate change.
3. Also, it is recommended that this assessment be used as a baseline from which general learnings about climate change vulnerability can be derived through comparing and contrasting results with those from other resource road assessments.

Tum Tum FSR

The PIEVC protocol directs that recommendations based on the risk and vulnerability assessment be assigned to five major categories:

- Remedial (engineering or operations) 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.
- There are gaps in data availability or data quality that require further work.

The vulnerability assessment of the Tum Tum FSR utilized a broad level analysis to the infrastructure along the 54 km length of the road chosen for the case study. The broad level analysis enabled the assessment team to make generalized evaluations of the risks for each of the infrastructure components. This approach, however, is unable to make specific statements regarding site specific infrastructure or to perform an engineered analysis of a specific infrastructure component or location on its resiliency to climate change. Considering this, this case study should be considered as a screening process of potential resource road vulnerabilities rather than specific design recommendations.

The following section presents recommended actions arising from the PIEVC assessment of the Tum Tum FSR. For reasons of brevity, the discussion is preliminary and general in nature, and focused only on highly or moderately vulnerable infrastructure identified by the PIEVC assessment.

Remedial actions

4. The Tum Tum FSR stakeholders are recommended to initiate ongoing maintenance activities as concerned for all bridges, major and minor culverts and cross drains. All stream crossings structures and cross drains were assessed to have medium-low or medium high risks to selected rainfall events. The professional opinions and experience of the assessment and advisory teams determined that these structures are likely at a higher risk for full or partial failure given local experience. Given this, the stakeholders should initiate ongoing maintenance activities to ensure that current design capacity and performance are provided until such time that a detailed inspection plan and design capacity analysis can be completed.

Management actions

5. The Tum Tum FSR road managers and maintenance supervisors, supervisors of industrial operations that use the road, and representatives of the recreational opportunities should review this report and become familiar with the climate change predictions for the Tum Tum FSR area and how these are likely to impact the performance of vulnerable infrastructure components. They should also read (Partington et al., 2017) for an extensive discussion of climate change adaptation measures for resource road infrastructure.
6. There are a number of minor culverts located along the Tum Tum FSR and this class of stream crossings were determined to be at low-medium or high-medium risk to predict future levels of some types of weather events. Road stakeholders should develop an inspection protocol and maintenance plan to ensure these structures perform to their design hydraulic capacities. Minor culverts are not usually designed for the stream flow parameters of each different crossing but, rather, the pipe diameters are selected according to local experience, cost, and (or) a provincial standard. As such, minor culverts have been found to be more vulnerable to plugging by debris and bedload transported during extreme storm flows. These structures should be specifically reviewed to determine their ability to accommodate forecasted climate changes, and to ensure the engineered and hydrologic design principles are implemented for any upgraded replacement structures.
7. A maintenance protocol should be developed and implemented for all water crossings (major and minor culverts, bridges) and cross drains to ensure these structures perform to their current design requirements. This protocol should include direction on maintenance frequency and action triggers and details on recommended maintenance actions and practices.
8. A performance inspection protocol should be developed and implemented for all water crossings (major and minor culverts, bridges) and cross drains to ensure these structures perform to their current design requirements. This will provide site date that can be used to determine future design needs and risks and vulnerabilities to required performance.
9. Commercial access and emergency response was determined to have a low-medium to high-medium risk to some climate parameters in both current and future periods. Considering the high level of industrial and recreational use of the road, contingency plans to provide medical support, supplies and communications, and emergency access in the case of bad weather and loss of access should be reviewed in light of the predicted climate changes and infrastructure vulnerabilities.

10. The spring thaw period was estimated to begin 10 days earlier in the future as compared to current trends. Although not specifically evaluated in this case study, this change may constrain late winter forest harvesting and transportation activities. In response, resource extraction in the late winter may need to be re-scheduled. Companies may consider the adoption of low-impact extraction practices or new, road-friendly, truck technologies to ensure that the risk is mitigated. The Tum Tum FSR industrial stakeholders should consider this impact in their long-term forest management access planning.

Additional study or acquisition of further data

11. The Tum Tum FSR stakeholders should expand efforts to gather details about weather events that coincide with peak stream flows and infrastructure failures. Increasing the understanding of how local weather impacts stream flows and infrastructure performance will empower managers, designers, and maintainers to reduce the vulnerability of road infrastructure and control risk associated with local climate changes.

12. An infrastructure inventory database should be created for the Tum Tum FSR that captures all of its infrastructure components, including the numerous cross drains and minor culverts that are not currently inventoried. This lack of asset data impedes the ability to achieve climate change resiliency for the road.

13. The Tum Tum FSR stakeholders should implement a process to document road performance details, such as maintenance activities, road usage, and traffic levels, so that this knowledge is retained after experienced staff retire from the workforce. This process also would ensure that maintenance activities and future road designs are optimized by being based on comprehensive and detailed records of road performance.

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9. APPENDIX A – PIEVC SPREADSHEET FOR THE BASELINE (2011-2040) PERIOD

Infrastructure Components and Operational Considerations	1					2				
	Drought conditions					**Daily temperature variation**				
	Days with drought code from very high to severe @ mid elevation				wildfire hazard, increased runoff from hydrophobic soils, dusty conditions	**Days with daily temperature variation > 25 °C @ road elevation**				**Relevance to Bridges** Thermal Expansion/Contraction
	Y/N	P	S	R		Y/N	P	S	R	
Road Prism Features										
Road surface	Y	6	2	12		Y	5	1	5	
Cut and fill slope	Y	6	1	6		Y	5	1	5	
Ditches & cross ditches	Y	6	0			Y	5	1	5	
Catch basins	Y	6	0			Y	5	1	5	
Cross drains	Y	6	0			Y	5	0		
Stream Crossings										
Major culverts > 1.8 m	Y	6	0			Y	5	0		
Other culverts < 1.8 m	Y	6	0			Y	5	0		
Bridges	Y	6	1	6		Y	5	1	5	
Upslope/Downslope beyond road prism										
Managed (Upper Adams Park)	Y	6	2	12		Y	5	0		
Unmanaged	Y	6	2	12		Y	5	0		
Operational Considerations										
Commercial and recreational access	Y	6	4	24		Y	5	0		
Emergency response	Y	6	3	18		Y	5	0		
Winter maintenance	N					Y	5	0		
Summer maintenance	Y	6	2	12		Y	5	0		
Personnel	Y	6	3	18		Y	5	0		

Infrastructure Components and Operational Considerations	3					4				
	Freeze/Thaw Cycling					**Cold Spells**				
	Days when T_{max} > 0 °C and T_{min} < 0 °C @ mid elevation				Laminar ice build up occurs on watercourses and ditches. Rock/ice fall onto road prism related to freeze/thaw.	**Periods with 7 days continuous maximum temperature < -5 ° C @ mid elevation**				Water coming to the surface and freezing creates (1) ice build-up on rock faces resulting in rock and ice fall onto road prism (2) ice build up in ditches, culverts and crossdrains resulting in blockage.
	Y/N	P	S	R		Y/N	5	S	R	
Road Prism Features										
Road surface	Y	7	1	7		Y	5	1	5	
Cut and fill slope	Y	7	1	7		Y	5	1	5	
Ditches & cross ditches	Y	7	3	21		Y	5	1	5	
Catch basins	Y	7	2	14		Y	5	3	15	
Cross drains	Y	7	2	14		Y	5	3	15	
Stream Crossings										
Major culverts > 1.8 m	Y	7	3	21		Y	5	1	5	
Other culverts < 1.8 m	Y	7	3	21		Y	5	3	15	
Bridges	Y	7	3	21		Y	5	1	5	
Upslope/Downslope beyond road prism										
Managed (Upper Adams Park)	Y	7	1	7		Y	5	1	5	
Unmanaged	Y	7	1	7		Y	5	1	5	
Operational Considerations										
Commercial and recreational access	Y	7	2	14		Y	5	2	10	
Emergency response	Y	7	2	14		Y	5	1	5	
Winter maintenance	Y	7	3	21		Y	5	3	15	
Summer maintenance	N					N				
Personnel	Y	7	2	14		Y	5	0		

Infrastructure Components and Operational Considerations	5					6				
	Spring Thaw					**Extreme High Rainfall in 24 hour period**				
	Thawing index; day of year CTI > 15 @ road elevation				Weak and thawing road conditions, no or spring load restricted (SLR) heavy traffic only.	**1-day rainfall > 65 mm @ high elevation**				High runoff. Culvert and bridge damage or destruction, road surface damage or deterioration, safety
	Y/N	P	S	R		Y/N	P	S	R	
Road Prism Features										
Road surface	Y	7	4	28		Y	4	3	12	
Cut and fill slope	Y	7	1	7		Y	4	3	12	
Ditches & cross ditches	Y	7	1	7		Y	4	3	12	
Catch basins	Y	7	1	7		Y	4	2	8	
Cross drains	Y	7	1	7		Y	4	5	20	
Stream Crossings										
Major culverts > 1.8 m	Y	7	1	7		Y	4	4	16	
Other culverts < 1.8 m	Y	7	1	7		Y	4	5	20	
Bridges	Y	7	1	7		Y	4	6	24	
Upslope/Downslope beyond road prism										
Managed (Upper Adams Park)	Y	7	1	7		Y	4	3	12	
Unmanaged	Y	7	1	7		Y	4	2	8	
Operational Considerations										
Commercial and recreational access	Y	7	4	28		Y	4	5	20	
Emergency response	Y	7	1	7		Y	4	5	20	
Winter maintenance	Y	7	1	7		N				
Summer maintenance	N					Y	4	3	12	
Personnel	Y	7	0			Y	4	3	12	

Infrastructure Components and Operational Considerations	7					8				
	Sustained Rainfall					**Antecedent rain followed by significant rain event**				
	3-day rainfall > 115 mm @ high elevation				High runoff. Culvert and bridge damage or destruction, road surface damage or deterioration, safety	**14-day antecedent rainfall > 80 mm followed by 1-day rainfall > 30 mm @ high elevation**				High runoff and saturated soils. Impacts to cut/fill slopes, landslides. Culvert and bridge damage or destruction, road surface damage or deterioration, safety.
	Y/N	P	S	R		Y/N	P	S	R	
Road Prism Features										
Road surface	Y	3	3	9		Y	6	3	18	
Cut and fill slope	Y	3	3	9		Y	6	3	18	
Ditches & cross ditches	Y	3	3	9		Y	6	3	18	
Catch basins	Y	3	2	6		Y	6	2	12	
Cross drains	Y	3	5	15		Y	6	5	30	
Stream Crossings										
Major culverts > 1.8 m	Y	3	4	12		Y	6	4	24	
Other culverts < 1.8 m	Y	3	5	15		Y	6	5	30	
Bridges	Y	3	6	18		Y	6	6	36	
Upslope/Downslope beyond road prism										
Managed (Upper Adams Park)	Y	3	3	9		Y	6	3	18	
Unmanaged	Y	3	2	6		Y	6	2	12	
Operational Considerations										
Commercial and recreational access	Y	3	5	15		Y	6	5	30	
Emergency response	Y	3	5	15		Y	6	5	30	
Winter maintenance	N					N				
Summer maintenance	Y	3	3	9		Y	6	3	18	
Personnel	Y	3	3	9		Y	6	3	18	

Infrastructure Components and Operational Considerations	9					10				
	Rapid Snow Melt (not with rain)					**Ice / Ice Jams**				
	1-day snow melt > 30 mm @ high elevation				Spring freshet conditions causing runoff and peak streamflow. Culvert and bridge damage or destruction, safety.	**Observed frequency of ice jammed in the river**				Road blockage and/or flooding, uncontrolled erosion, unplanned closures.
	Y/N	P	S	R		Y/N	P	S	R	
Road Prism Features										
Road surface	Y	6	1	6		Y	2	3	6	
Cut and fill slope	Y	6	1	6		Y	2	0		
Ditches & cross ditches	Y	6	2	12		Y	2	2	4	
Catch basins	Y	6	2	12		Y	2	0		
Cross drains	Y	6	2	12		Y	2	3	6	
Stream Crossings										
Major culverts > 1.8 m	Y	6	2	12		Y	2	0		
Other culverts < 1.8 m	Y	6	3	18		Y	2	0		
Bridges	Y	6	3	18		Y	2	0		
Upslope/Downslope beyond road prism										
Managed (Upper Adams Park)	Y	6	1	6		Y	2	0		
Unmanaged	Y	6	1	6		Y	2	0		
Operational Considerations										
Commercial and recreational access	Y	6	1	6		Y	2	3	6	
Emergency response	Y	6	1	6		Y	2	3	6	
Winter maintenance	Y	6	2	12		Y	2	3	6	
Summer maintenance	N	6	0			N				
Personnel	Y	6	1	6		Y	2	3	6	

Infrastructure Components and Operational Considerations	11					12				
	Snow Frequency					**Snow Accumulation**				
	Days with > 10 cm of precipitation as snow (T_{avg} < 1 °C) @ mid elevation				Snow plowing resulting in increased risk to damage of infrastructure.	**Days with a snow depth > 60 cm @ mid elevation**				Measure of how much snow accumulates on road edges due to snowfall and from snow plowing resulting in increased risk to damage to signs and barriers. Snow on hills above road.
	Y/N	P	S	R		Y/N	P	S	R	
Road Prism Features										
Road surface	Y	5	2	10		Y	7	2	14	
Cut and fill slope	Y	5	2	10		Y	7	2	14	
Ditches & cross ditches	Y	5	1	5		Y	7	1	7	
Catch basins	Y	5	1	5		Y	7	1	7	
Cross drains	Y	5	0			Y	7	0		
Stream Crossings										
Major culverts > 1.8 m	Y	5	0			Y	7	0		
Other culverts < 1.8 m	Y	5	0			Y	7	0		
Bridges	Y	5	3	15		Y	7	3	21	
Upslope/Downslope beyond road prism										
Managed (Upper Adams Park)	Y	5	0			Y	7	1	7	
Unmanaged	Y	5	0			Y	7	1	7	
Operational Considerations										
Commercial and recreational access	Y	5	1	5		Y	7	1	7	
Emergency response	Y	5	1	5		Y	7	1	7	
Winter maintenance	Y	5	2	10		Y	7	2	14	
Summer maintenance	N	5	0			N	7	0		
Personnel	Y	5	1	5		Y	7	1	7	

10. APPENDIX B – PIEVC SPREADSHEET FOR THE FUTURE (2041-2070) PERIOD

	1					2					3					4					5					6				
Infrastructure Components and Operational Considerations	**Drought conditions**					**Daily temperature variation**					**Freeze/Thaw Cycling**					**Cold Spells**					**Spring Thaw**					**Extreme High Rainfall in 24 hour period**				
	Days with drought code from very high to severe @ mid elevation				wildfire hazard, increased runoff from hydrophobic soils, dusty conditions	**Days with daily temperature variation > 25 °C @ road elevation**				**Relevance to Bridges** Thermal Expansion/Contraction	**Days when T_{max} > 0 °C and T_{min} < 0 °C @ mid elevation**				Laminar ice build up occurs on watercourses and ditches. Rock/ice fall onto road prism related to freeze/thaw.	**Periods with 7 days continuous maximum temperature < -5 ° C @ mid elevation**				Water coming to the surface and freezing creates (1) ice build-up on rock faces resulting in rock and ice fall onto road prism (2) ice build up in ditches, culverts and crossdrains resulting in blockage.	**Thawing index; day of year CTI > 15 @ road elevation**				Weak and thawing road conditions, no or spring load restricted (SLR) heavy traffic only.	**1-day rainfall > 65 mm @ high elevation**				High runoff. Culvert and bridge damage or destruction, road surface damage or deterioration, safety
	Y/N	P	S	R		Y/N	P	S	R		Y/N	P	S	R		Y/N	5	S	R		Y/N	P	S	R		Y/N	P	S	R	
Road Prism Features																														
Road surface	Y	6	2	12		Y	5	1	5		Y	7	1	7		Y	5	1	5		Y	7	4	28		Y	5	3	15	
Cut and fill slope	Y	6	1	6		Y	5	1	5		Y	7	1	7		Y	5	1	5		Y	7	1	7		Y	5	3	15	
Ditches & cross ditches	Y	6	0			Y	5	1	5		Y	7	3	21		Y	5	1	5		Y	7	1	7		Y	5	3	15	
Catch basins	Y	6	0			Y	5	1	5		Y	7	2	14		Y	5	3	15		Y	7	1	7		Y	5	2	10	
Cross drains	Y	6	0			Y	5	0			Y	7	2	14		Y	5	3	15		Y	7	1	7		Y	5	5	25	
Stream Crossings																														
Major culverts > 1.8 m	Y	6	0			Y	5	0			Y	7	3	21		Y	5	1	5		Y	7	1	7		Y	5	4	20	
Other culverts < 1.8 m	Y	6	0			Y	5	0			Y	7	3	21		Y	5	3	15		Y	7	1	7		Y	5	5	25	
Bridges	Y	6	1	6		Y	5	1	5		Y	7	3	21		Y	5	1	5		Y	7	1	7		Y	5	6	30	
Upslope/Downslope beyond road prism																														
Managed (Upper Adams Park)	Y	6	2	12		Y	5	0			Y	7	1	7		Y	5	1	5		Y	7	1	7		Y	5	3	15	
Unmanaged	Y	6	2	12		Y	5	0			Y	7	1	7		Y	5	1	5		Y	7	1	7		Y	5	2	10	
Operational Considerations																														
Commercial and recreational access	Y	6	4	24		Y	5	0			Y	7	2	14		Y	5	2	10		Y	7	4	28		Y	5	5	25	
Emergency response	Y	6	3	18		Y	5	0			Y	7	2	14		Y	5	1	5		Y	7	1	7		Y	5	5	25	
Winter maintenance	N					Y	5	0			Y	7	3	21		Y	5	3	15		Y	7	1	7		N				
Summer maintenance	Y	6	2	12		Y	5	0			N					N					N					Y	5	3	15	
Personnel	Y	6	3	18		Y	5	0			Y	7	2	14		Y	5	0			Y	7	0			Y	5	3	15	

	7					8					9					10					11					12				
Infrastructure Components and Operational Considerations	**Sustained Rainfall**					**Antecedent rain followed by significant rain event**					**Rapid Snow Melt (not with rain)**					**Ice / Ice Jams**					**Snow Frequency**					**Snow Accumulation**				
	3-day rainfall > 115 mm @ high elevation				High runoff. Culvert and bridge damage or destruction, road surface damage or deterioration, safety	**14-day antecedent rainfall > 80 mm followed by 1-day rainfall > 30 mm @ high elevation**				High runoff and saturated soils. Impacts to cut/fill slopes, landslides. Culvert and bridge damage or destruction, road surface damage or deterioration, safety.	**1-day snow melt > 30 mm @ high elevation**				Spring freshet conditions causing runoff and peak streamflow. Culvert and bridge damage or destruction, safety.	**Observed frequency of ice jammed in the river**				Road blockage and/or flooding, uncontrolled erosion, unplanned closures.	**Days with > 10 cm of precipitation as snow (T_{avg} < 1 °C) @ mid elevation**				Snow plowing resulting in increased risk to damage of infrastructure.	**Days with a snow depth > 60 cm @ mid elevation**				Measure of how much snow accumulates on road edges due to snowfall and from snow plowing resulting in increased risk to damage to signs and barriers. Snow on hills above road.
	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	
Road Prism Features																														
Road surface	Y	4	3	12		Y	6	3	18		Y	6	1	6		Y	2	3	6		Y	5	2	10		Y	6	2	12	
Cut and fill slope	Y	4	3	12		Y	6	3	18		Y	6	1	6		Y	2	0			Y	5	2	10		Y	6	2	12	
Ditches & cross ditches	Y	4	3	12		Y	6	3	18		Y	6	2	12		Y	2	2	4		Y	5	1	5		Y	6	1	6	
Catch basins	Y	4	2	8		Y	6	2	12		Y	6	2	12		Y	2	0			Y	5	1	5		Y	6	1	6	
Cross drains	Y	4	5	20		Y	6	5	30		Y	6	2	12		Y	2	3	6		Y	5	0			Y	6	0		
Stream Crossings																														
Major culverts > 1.8 m	Y	4	4	16		Y	6	4	24		Y	6	2	12		Y	2	0			Y	5	0			Y	6	0		
Other culverts < 1.8 m	Y	4	5	20		Y	6	5	30		Y	6	3	18		Y	2	0			Y	5	0			Y	6	0		
Bridges	Y	4	6	24		Y	6	6	36		Y	6	3	18		Y	2	0			Y	5	3	15		Y	6	3	18	
Upslope/Downslope beyond road prism																														
Managed (Upper Adams Park)	Y	4	3	12		Y	6	3	18		Y	6	1	6		Y	2	0			Y	5	0			Y	6	1	6	
Unmanaged	Y	4	2	8		Y	6	2	12		Y	6	1	6		Y	2	0			Y	5	0			Y	6	1	6	
Operational Considerations																														
Commercial and recreational access	Y	4	5	20		Y	6	5	30		Y	6	1	6		Y	2	3	6		Y	5	1	5		Y	6	1	6	
Emergency response	Y	4	5	20		Y	6	5	30		Y	6	1	6		Y	2	3	6		Y	5	1	5		Y	6	1	6	
Winter maintenance	N					N					Y	6	2	12		Y	2	3	6		Y	5	2	10		Y	6	2	12	
Summer maintenance	Y	4	3	12		Y	6	3	18		N	6	0			N					N	5	0			N	6	0		
Personnel	Y	4	3	12		Y	6	3	18		Y	6	1	6		Y	2	3	6		Y	5	1	5		Y	6	1	6	

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