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A CLIMATE CHANGE VULNERABILITY ASSESSMENT APPROACH FOR RESOURCE ROADS

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February 2020

ABSTRACT:

Given the benefits that resource roads provide to economic and social well-being, it is important to understand the impacts of a changing climate on resource roads and infrastructure. As the forest industry and governments move toward creating resource roads that are resilient to climate change, an early step in the adaptive management process is to assess the risks and vulnerabilities of infrastructure to climate change.

301013535: CLIMATE CHANGE AND ENVIRONMENTAL IMPACTS

TECHNICAL REPORT – 2020-08

ACKNOWLEDGEMENTS
This project was financially supported by Natural Resources Canada under the NRCan/FPInnovations Contribution Agreement and by the Province of British Columbia under the B.C. – FPInnovations Innovation Strategy.

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BACKGROUND

The recommendations in this report were developed through the completion of three case studies on risk and vulnerability to climate change completed by FPInnovations on resource roads in British Columbia (Bradley & Forrester, 2018; Partington & Bradley, 2019; Partington, Durand-Jézéquel & Bradley, 2018). The case studies were based primarily on the protocol developed by the Public Infrastructure and Engineering Vulnerability Committee (PIEVC) for assessing the vulnerability of public infrastructure to a changing climate. The PIEVC protocol, in addition to additional frameworks and resources, are recommended to be reviewed before implementing a resource road climate change vulnerability assessment:

- Association of Professional Engineers & Geoscientists of British Columbia (APEGBC). (2016). *Developing climate change-resilient designs for highway infrastructure in British Columbia* (Version 1.0).
- Engineers Canada. (2016). *PIEVC engineering protocol for infrastructure vulnerability assessment and adaptation to a changing climate: Principles and guidelines* (Version PG-10.1).
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INTRODUCTION

Managing resource roads and infrastructure continues to be important for industries and governments across Canada. Planning, construction, and maintenance of resource roads must support various industrial and resource management activities; these roads are also often the primary access routes for remote communities and public recreation. Given the benefits that resource roads provide to economic and social well-being, it is important to understand the implications of climate change to adapt these roads and infrastructure to the impacts of a changing climate.

As the forest industry and governments move toward creating resource roads that are resilient to climate change, an early step in the process is to assess the extent to which climate change may impact resource road infrastructure. The process of identifying the risks is an important early step in the adaptation process (Figure 1). Adapting resource roads and infrastructure to the effects of climate change involves understanding the risks and vulnerabilities, identifying infrastructure elements where risks are greatest, and creating a strategy to ensure that the road and infrastructure elements are made resilient.

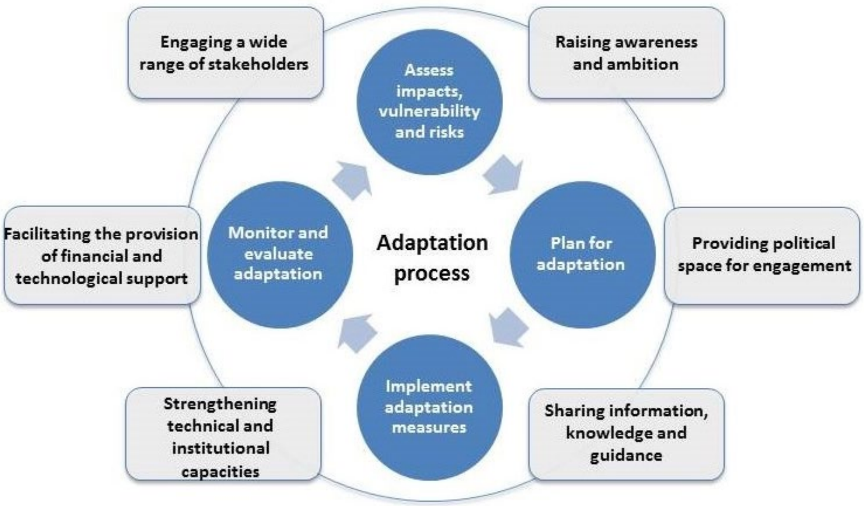

Figure 1. The climate change adaptation management cycle. (Adapted from the United Nations Framework Convention on Climate Change.)

A risk assessment, when performed early in the adaptation management process, can provide valuable information to support effective decision making for the immediate to long-term management of resource road infrastructure. Information gained through an assessment process can identify the following:

- The infrastructure that is at the highest risk to the effects of a forecasted changing climate.
- The climate events that are forecasted to generate the greatest risks to infrastructure management.
- Areas where resources and investments should be made to develop a resilient resource road network.
- Research and technology needs for updating infrastructure design requirements.

Based heavily on the approach and recommendations of the PIEVC protocol, this report provides the recommendations and considerations for applying a vulnerability assessment to resource roads. More specifically, this report:

- Outlines a suggested approach for implementing a climate change risk and vulnerability assessment for resource roads.
- Provides guidance on the resource road infrastructure elements and climate parameters to consider in the assessment.
- Recommends an approach to implement results and considerations for next steps after the assessment is completed.

ADAPTATION AND RESILIENCY

Adaptation

Climate change adaptation refers to any action that reduces the negative impacts of climate change and reduces the vulnerability of the value that is under management – in this case, resource roads and infrastructure. Adapting resource roads and infrastructure to climate change includes any administrative, policy, standards, planning, design, maintenance, or construction activity that is implemented to address the projected changes in climate.

Adaptation provides a means by which climate change impacts are mitigated and vulnerability reduced through the implementation of practices or tools. For resource roads and infrastructure, adaptation can be classified as operational (changes to policies or procedures) or structural (direct changes to infrastructure).

Implementing adaptation practices does not necessarily require significant changes to resource road management. Many current practices that ensure resource roads function to the required service levels may also be considered practices toward climate change adaptation. For example, effective erosion control and slope stabilization practices are already commonly implemented best management practices. If a changing climate is forecasted to result in an increase in short-duration, high-intensity rainfall events, minor changes to the design specifications of the current standard practices for slope stabilization may sufficiently account for changes in peak flows and soil erosion events. Other adaptation practices might require more significant changes to current resource road usage under certain climate forecasts. Milder winters and increased rain-on-snow events are expected in some regions of Canada, which could reduce the use of winter-only roads and would require significant adaptations in road construction and maintenance to allow for continued road use.

Resiliency

Through the implementation of climate change adaptation practices, a resilient resource road infrastructure and network system can be created. Resource road infrastructure resiliency is the "capacity to withstand disruption, absorb disturbance, act effectively in a crisis, adapt to changing conditions and transform over time" (Hughes & Healy, 2014).

It is important to remember that the intent is not to create infrastructure that is resistant to all hazards. Rather, the intent is to create infrastructure that has the capacity to respond and adapt to climate change hazards and events while reducing the severity of damage.

Long-term climate forecasting with the current climatic models utilizes a coarse landscape approach and is, therefore, best suited for analyzing the impacts on large geographic areas. For many engineers, designers, and planners of resource roads, there is a desire for climate predictions for specific operating areas. Given the limitations in the modelling and data used in forecast development, there are uncertainties in the application of models for specific weather events and conditions for local areas. Given these uncertainties, it can be difficult to design and construct a road that is fully resistant to failures and hazards resulting from climate change.

RISK AND VULNERABILITY

To adapt resource roads to climate change, vulnerabilities and risks must be identified. Vulnerability is defined as an indication of the degree to which infrastructure is susceptible or unable to cope with the negative impacts of climate change. Vulnerability to climate change is generally considered to be a function of the following three factors (Intergovernmental Panel on Climate Change, 2014):

1. Exposure: the degree to which resource roads and infrastructure are forecasted to be exposed to climate change.
2. Sensitivity: the level or extent to which resource roads will be affected by a change in climate events.
3. Adaptive capacity: the ability of resource roads and infrastructure to adapt to the negative impacts of the forecasted changes in climate.

In general, a vulnerability assessment can be wide-ranging and can include impacts not only to road infrastructure function but also to the environmental and community values that the road supports or is affected by. Including all these factors into a vulnerability assessment can be challenging for road managers and would require involving professional specialists and community members. For this reason, the assessment process outlined here focuses on the operability and function of infrastructure, known as engineering vulnerability. This allows for the assessment team to focus on those factors that are under the team's direct control and that can be responded to in a focused manner.

Once the vulnerability is identified, an evaluation is performed to understand the risks to the system. When evaluating the risks of climate change, the probability of a negative impact must be considered, in addition to the severity of the impact if the event occurs. This may be best accomplished through a formal risk management process. In this case, the process considers and evaluates the exposure, sensitivity, adaptive capacity, and adaptation measures to resource road and infrastructure (Figure 2).

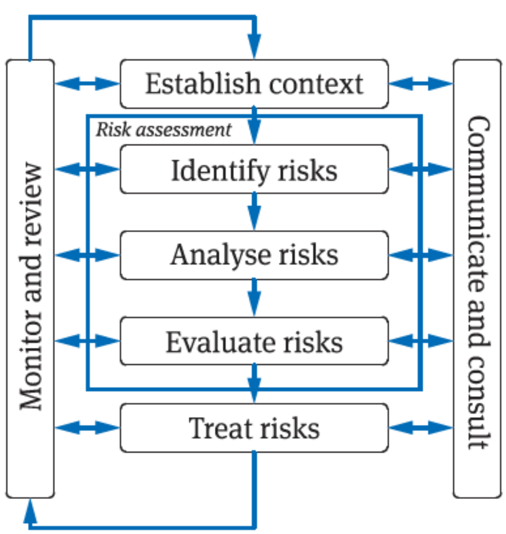

Figure 2. The risk management process. (Adapted from International Organization for Standardization, 2009.)

Risk assessment protocols

Various protocols are available to assess the vulnerability of infrastructure to climate change (Rasmussen, Lamoureux, Simmons, & Miller, 2018; Filosa, Plovnick, Stahl, Miller, & Pickrell, 2017); however, the PIEVC protocol is the method commonly used in Canada (Engineers Canada, 2016). The protocol is a civil engineering tool used for assessing the vulnerability of engineered structures to climate change.

The PIEVC created a five-step protocol to assess various infrastructure elements, while focusing on public and civil infrastructure; it also can be adapted to resource roads and infrastructure (Figure 3).

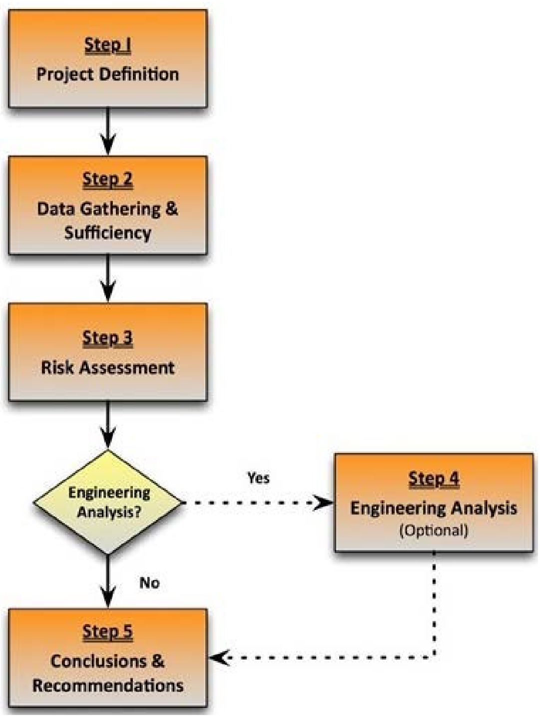

Figure 3. Stages in the PIEVC protocol. (Reproduced from Engineers Canada, 2016.)

The PIEVC protocol, as well as other common risk and vulnerability frameworks, 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. The application and fulfillment of a vulnerability assessment relies on a team approach and on the professional judgment of those involved in the assessment. The emphasis is placed on identifying practical approaches to reducing vulnerability within an established schedule and budgetary constraints.

Assessment approach for resource roads

The PIEVC protocol is an engineering approach that is often conducted for specific, well-defined types of infrastructure, such as a sewage or water treatment plant, municipal assets, a bridge, etc. However, it also can be applied on a regional or network level, where classes of infrastructure are assessed. This type of approach has been used for provincial highway networks (BGC Engineering, 2011; Nodelcorp Consulting Inc., 2011) and is the approach recommended for resource road assessments. The broad-level management approach that is often taken for resource roads creates a condition for which site- or infrastructure-specific vulnerability assessments offer too narrow a focus. For this reason, it is recommended that a vulnerability assessment on a resource road consider the risks for given classes of infrastructure on a given segment of road or area of interest rather than for specific infrastructure sites. For example, with this approach, the assessment process could recommend that water-crossing structures be sized larger to accommodate an increase in peak flows to reduce the forecasted climate risks, rather than stating an amount of increase required for a specific water crossing location.

ENSURING SUCCESS

Completing a vulnerability assessment can be a daunting task and can stretch timelines and budgets if adequate planning and resources are not assigned from the outset. If efficiently managed and designed, however, a vulnerability assessment can be a valuable exercise that aids in developing resilient resource roads and can be useful in short- to long-term operational and financial planning.

This report outlines a framework for performing a vulnerability assessment, but the following specific items are important to recognize to ensure success:

1. Clearly define the scope.
2. Achieve agreement on the objectives of the assessment.
3. Focus on the most relevant infrastructure to achieving a resilient road.
4. Target the most crucial climate parameters that highlight the key climate events.
5. Document the process and write a clear and concise final report.

RISK ASSESSMENT FRAMEWORK

Based primarily on the PIEVC approach, a review of other common frameworks and the lessons from three risk assessment case studies FPInnovations performed in B.C. (Bradley & Forrester, 2018; Partington & Bradley, 2019; Partington, Durand-Jézéquel & Bradley, 2018), the process presented in Figure 4 is the approach recommended for determining the climate change risks to resource roads.

Figure 4. Suggested steps for a vulnerability assessment for resource roads.

Step 1. Determine the scope and study parameters

Determining the scope, parameters, and objectives is the first step to ensuring a successful vulnerability assessment. An assessment that is clearly defined and articulated allows for an efficient process that provides results and clarifies the value that participants have in developing resilient resource roads. In this step, the following questions must be addressed:

- Why is the assessment being performed?
- What are the overall objectives of the assessment?
- What are the expected or desired outcomes?
- How will the outcomes of the assessment be used?
- What skill sets are needed, and which individuals will participate in the assessment?
- Which region or roads will be included in the study?
- What is the budget and completion date for the assessment?

Setting the objectives is best performed by dedicated individuals on the assessment team. The assessment team should consist of a diverse group of individuals, including, but not limited to:

- The principal road users who are familiar with the road use, maintenance practices, and historical issues related to extreme weather events.
- Stakeholders, including government and secondary road users who have an interest, and perhaps a responsibility, for the management of the road(s).
- Climatologists familiar with local weather patterns, and capable of deriving current and future weather variables and thresholds from data sources.
- Engineering specialists, such as hydrologists and geotechnical engineers, familiar with local landforms and the effects of extreme weather events in the area.
- Facilitator to guide the discussions and direct the assessment team through the process.

For a balanced approach to determining the risk profiles in the assessment, the individuals representing the above groups should offer diverse skill sets and disciplines. Depending on the scope of the assessment, an advisory team may be formed, consisting of additional individuals who may be called upon to provide professional feedback and opinions on certain aspects of the assessment.

In this step, the assessment team must determine the geographic scope and/or the road segments or classes to include in the assessment. Various approaches may be used to determine the geographic scope, and these depend on the objectives and interests of the assessment team. A high-level approach may consider all road types within a given geographic area that ideally have similar landscape conditions, such as elevation. A localized approach may also be considered if the assessment team wants to assess a specific road segment that serves as a critical access corridor, or where ongoing performance issues have been identified.

Step 2. Identify infrastructure elements and their present condition

Resource road infrastructure can comprise various elements of a road network and refers to any fixed asset that provides for the operation of equipment and vehicles on the road. For example, the types of infrastructure considered part of a resource road include signage, bridges, culverts, the road prism and road surface, engineering works, cut slopes, and fill slopes.

Given the broad-level management approach and relatively low-traffic levels common on resource roads, prioritizing infrastructure elements to be included in a climate change risk and vulnerability assessment can aid in bringing efficiency and focus to the assessment.

Assessment teams may also consider including additional operational elements, such as road usage, operational considerations and environmental values, if the team believes that these elements may be a priority for future resource road management. Road usage issues such as spring load restrictions or access considerations can be critical elements that are affected by forecasted changes in the climate. Including these operational elements may provide the assessment team with indicators that are relevant to future operational, access, and safety considerations for a road’s industrial and recreational users.

It is generally recommended that environmental values not be included within the scope of a resource road risk assessment and that they be addressed through supplemental initiatives instead. Assigning the severity of climate impacts to environmental values can be a challenge and is subject to considerable judgement and interpretation. To make these assignments the assessment team may also need to rely on the input and expertise of additional individuals whose expertise and interests lie outside the scope of the assessment.

If the assessment team determines that environmental values should be included in the assessment, it is recommended that the scope of the environmental element be clearly defined and that it be specified how the road may interact with the environmental element, both currently and in the future. In addition, rather than including a broad-value element, such as fish habitat, it is recommended that the assessment identify a high-value location or area of special concern, such as a section of road that passes through a managed park.

The types of infrastructure and operational considerations that are recommended for inclusion in a risk analysis are presented in Appendix A. This list includes only those elements that were identified as being most impacted by extreme weather events in three assessments of resource roads (Partington & Bradley, 2019; Partington, Durand-Jézéquel & Bradley, 2018; Bradley & Forester, 2018). The list is not comprehensive and could be expanded by the assessment team to include other elements that are present on the subject road(s) and judged to be of critical concern. Included in Appendix A are the projected impacts from a failure to element condition and function. The possible infrastructure elements can be divided into three categories:

1. Road features, including the road prism, cut and fill slopes, cross drains, and ditches.
2. Stream crossings, including bridges and other major structures (e.g., culverts and arches) and minor structures (i.e., small culverts).
3. Operational considerations, including access, emergency response, winter and summer maintenance/construction, and safety.

At this stage in the process, the assessment team should also gather information and data on the infrastructure elements that have been selected for inclusion in the assessment. This information will help the assessment team to determine the sensitivity of the infrastructure to changes in the identified climate parameters chosen later in the assessment process and the impact of failures to the structure and surrounding values. Infrastructure data should include, but not be limited to, the following:

- Current and historical infrastructure maintenance plans and interventions.
- Location and inventory.
- Failure events of critical infrastructure (and the associated climate event).
- Changes in infrastructure design standards or government regulations influencing design approaches.
- Historical, current, and forecasted road usage, including the volume and types of traffic.

Step 3. Identify the climate parameters

Determining which climate parameters to include in an assessment can be one of the most difficult tasks for the assessment team. The climate parameters included in an assessment must be directly responsible for degradation or failure of road infrastructure and affect current road use and management strategies or are forecasted to become relevant to road use and management in the future. The following recommendations provide guidance about climate parameter selection and related actions:

1. Choose the climate parameters as early as possible in the assessment process to allow time for identifying or developing the required data.
2. Engage local road users in identifying historic weather events or conditions that generated road management challenges.
3. Consider including climate specialists in the assessment team to ensure proper interpretation and assignment of the climate data.
4. Minimize the number of climate parameters to ensure efficiency while still representing the critical conditions known to affect infrastructure function and serviceability.
5. Investigate the availability and application of existing climate data sets and information to be utilized in the assessment, where appropriate, rather than generating custom climate data. Generating custom climate data may not be possible within the confines of the assessment timelines and budgets, nor be necessary given the assessment objectives. There is an increasing amount of publicly available national, provincial, and regional climate modelling data and analysis being generated across the country.
6. In regions with mountainous terrain, consider climate data for the elevation of the road and for higher elevations within the watershed. This approach can help identify those parameters whose occurrence at higher elevations impact the events occurring at the road (e.g., stream flow, debris flows, avalanches).
7. If data cannot be found or generated to quantify the thresholds for a given climate parameter, use professional judgment and local experience to determine these threshold levels.
8. To allow others to use the results of the assessment, identify the source of the climate data in the assessment report.

The types of climate parameters that are recommended for inclusion in an assessment are presented in Appendix B. This list includes only those parameters that were identified as being of greatest interest in three assessments of resource roads (Partington & Bradley, 2019; Partington, Durand-Jézéquel & Bradley, 2018; Bradley & Forester, 2018). The list is not comprehensive and could be modified by the assessment team to include other climate parameters that occur in the area of study and are judged to be of critical concern. These parameters generally fall into three categories:

1. Temperature, including extended periods of drought, freeze/thaw action, and seasonal extremes.
2. Precipitation as rain, including sustained, high, and extreme rainfall events, and seasonal changes.
3. Precipitation as snow, including frequency and depths.

At this stage of the process, the assessment team should also decide the future time horizons to be considered for the analysis. The time horizons should reflect the design, usage, planning and service life of the infrastructure elements being considered in the assessment. The infrastructure element considerations can then be combined with the climate data availability and forecasting to determine the future time horizons to be included in the assessment.

Step 4. Determine the risks and vulnerabilities

At this stage of the process, the assessment team should determine the risk profiles, where risk is the result of the probability of an identified negative event (climate parameter) occurring, and the severity of the consequences of that event on the identified infrastructure element. When determining risk profiles, the assessment team should consider three general questions: (1) What can happen, (2) How likely is it to occur, and (3) What are the consequences to the infrastructure element.

Before determining risk, each combination of infrastructure element and climate parameter should be considered as to whether there is an interaction. For example, the climate parameter of drought condition would not be expected to interact with the operational consideration of winter maintenance. This interaction can be eliminated, therefore, from needing to be risk scored.

Once the climate and infrastructure interactions have been identified, the assessment team must determine the probability of an infrastructure element's capacity being exceeded by the climate parameter and the severity or consequences of the climate parameter exceeding the infrastructure element's capacity. Assigning probability and severity values allow the assessment team to develop a risk matrix, where each climate and infrastructure interaction is ranked or assigned a low-to-high risk profile.

Key items to consider at this stage are:

1. There is no single methodology to develop a risk matrix. To determine the approach that may work best for the assessment, review, amongst others, the approaches outlined by Rasmussen, Lamoureux, Simmons, & Miller, 2018; Filosa, Plovnick, Stahl, Miller, & Pickrell, 2017; Engineers Canada 2016.
2. Consider a simplified approach (low, medium, high) for categorizing the risk values in order to minimize time spent by the assessment team on the risk scoring and to focus the assessment on the high-risk interactions that are of the greatest importance in a generalized assessment approach recommended for resource roads.
3. Be aware of the sensitivity of the risk determined for each climate and infrastructure interaction. Consider performing a sensitivity analysis to determine how much the risk scores may change for each interaction if incremental changes are made to the probability or severity values.
4. Consider a facilitated workshop, where the interactions and risk scores are preliminarily assigned by the assessment team, as an efficient means of gathering feedback from all members of the team.
5. In addition, consider conducting a field visit, which can be a valuable opportunity for the assessment team to become familiar with the road conditions, historical issues, and general road management challenges.

Step 5. Review and finalize the results

After determining the risks, the assessment team must review the outcomes in consideration of the initial scope and objectives of the assessment. It is critical that the risk scores be reviewed and that they reflect the risk tolerance of all members of the assessment team. For example, in the occurrence of a bridge washout, team member's risk assignments may differ on whether an alternate route is available and on the route's condition. If the alternate route provides for light but not heavy vehicle traffic or is not needed to be used immediately by some road users, the risk tolerance will differ between assessment team members.

At this time, the assessment team should review the initial list of infrastructure elements to identify and address, if possible, missing information. If missing climate parameters and data gaps are identified after the assessment is complete, additional data should be generated and considered.

The assessment team may need to cycle through steps 4 and 5 of the assessment framework before reaching a conclusion that is acceptable to all members of the team. Achieving agreement from all team members for all risk scores may be difficult depending on the diversity and risk tolerance thresholds of individual members. If agreement cannot be reached and outstanding issues among team members remain, ensure that this is identified in the final report.

The assessment team may also want to consider performing a more detailed review of those infrastructure element and climate parameter interactions that have been identified as high risk. A further analysis may focus on the engineered design, climate variables or changes in future road usage or planning for specific infrastructure elements that will impact the risk profiles. A comprehensive review of the high-risk interactions will allow the assessment team to investigate a more complete list of adaptation options, if that is chosen to be included in the assessment, for the infrastructure element to accommodate future needs.

Step 6. Reporting

The final step in the framework is developing the risk assessment report. The report should reflect the assessment objectives, data and information considered, and risk results and discussion. While developing the final report, keep in mind the following:

1. The report should clearly indicate whether the infrastructure will be at risk due to forecasted changes in the climate parameters.
2. Include all the pertinent details that explain how the assessment was conducted and provide readers with enough information as to how the risk evaluation outcomes were achieved. This clarification is essential to support a future re-assessment, if management objectives or infrastructure use changes in the future.
3. Outline and discuss limitations to the scope or outcomes of the assessment, such as data gaps, assessment team representations, or restrictions in the scope of the assessment.
4. Include a detailed presentation of the risk scores and the summarized risks, by category, or in a risk matrix to allow readers to review the risk process details and understand the generalized prioritization of risks for given infrastructure and climate relationships.
5. Provide enough detail to support risk management decisions that may arise from the assessment, such as the need for infrastructure upgrades or replacement, actions to mitigate safety and environmental concerns, and regulatory and design changes related to the function and use of the resource road.
6. If the assessment team decides to include general or detailed adaptation practices to mitigate the risks identified in the assessment, ensure that these practices are prioritized based on the identified risks and,

possibly, categorized based on whether planning, management, or operational adaptation practices are indicated.

NEXT STEPS

Upon the completion of a climate change vulnerability assessment, the assessment team will have identified the risks and vulnerabilities to resource road infrastructure. This assessment process allows the opportunity to prioritize low, medium, and high risks and identify the climate and infrastructure interactions that are most critical to address when ensuring a resilient resource road network.

The scope of the assessment, often dictated by project budgets and timelines, will determine if the assessment will focus solely on identifying the risks or if it will proceed to identifying and evaluating the mitigation measures that allow the opportunity for the resource road to adapt to future climate conditions.

If the scope of the assessment is to focus only on the assessment of risks and vulnerabilities, it is important to state this as an objective in the final report. It is however, generally recommended that assessment teams consider integrating the identification and prioritization of adaptation measures to address the risks identified in the assessment outcomes into the final reporting. The primary objective of many assessments is to advance resource roads towards resiliency and this is achieved by identifying and implementing adaptation measures. A comprehensive review of adaptation measures and implementation approaches may be outside the scope, budget and timeline of the assessment, if so, the need for further study and evaluation should be a recommendation in the final report. It is essential to recognize the limitations and applications of the assessment and how it fits into the adaptation management and mainstreaming cycle. As stated by Nodelman (2019), “While risk assessment tends to give good insight, we can focus too narrowly on this one element of a robust risk management process.” A comprehensive review of adaptation strategies for resource roads are offered in Keller, G., & Ketcheson, G. (2015) and Partington, M., Bradley, A., Durand-Jézéquel, M., & Forrester, A. (2017).

Generally, the adaptation strategies that mitigate the impacts of climate change on resource roads result in higher-quality roads with increased performance levels, regardless of whether climate change occurs. A good example of this is the maintenance of cross drains and small culverts which, when done regularly, results in improved drainage, stronger and more stable roadbeds, and improved ability to pass storm flows and debris. With limited capital resources available for the planning, construction, and maintenance of resource roads, however, efforts and capital costs must be focused where adaptation strategies are most needed.

The approaches for adaptation can be broadly categorized into proactive and reactive adaptation strategies, and both may be considered as planned approaches to adaptation. Deciding which adaptation strategy (or strategies) to implement requires that the benefits from the strategy outweigh the potential costs of climate change–induced damage and the costs of implementing the strategy.

Proactive adaptation, also known as anticipatory adaptation, is a planned approach that maintains the infrastructure to its designed performance levels before deterioration occurs. This approach may be challenging to implement, as it requires an upfront investment in planning, forecasting, and maintenance or construction. This approach involves long-term decision making and climate forecasting to reduce the vulnerability of the infrastructure to climate change and to increase their resiliency. Proactive adaptation requires that current operational and safety practices and policies be carefully analyzed and assessed for their effectiveness under a changing climate.

Reactive adaptation, also known as a “wait and see” approach, is a planned approach wherein management responses occur after a structure has been damaged or destroyed, or its function or serviceability degraded. The risk inherent in a reactive adaptation approach is that the performance levels of the road are permitted to decrease, possibly below operational and safety thresholds.

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APPENDIX A

Table 1. List of infrastructure elements for consideration in an assessment

Infrastructure element or operational consideration	Description of infrastructure element	Impact of failure
Road features		
Road prism (surface/subgrade)	Running surface, road shoulders, subgrade	Road function, maintenance, safety, etc.
Cut and fill slope	Constructed slopes beside road	Road function, maintenance, drainage; can propagate to uphill or downhill areas
Ditches	Water drainage ditches alongside road	Road function, maintenance, drainage, downhill slope stability
Cross drains	Culverts in road to drain ditch water to opposite side of road	Road function, maintenance, drainage, downhill slope stability
Stream crossings		
Major culverts	Culvert diameter ≥ 2.0 m	Flooding, road prism washouts, structure loss, road closure
Other culverts	Culvert diameter < 2.0 m	Flooding, road prism washouts, structure loss, road closure
Bridges	All bridges	Road approach washouts, structure loss, road closure
Operational considerations		
Commercial, recreational, residential access	All industrial traffic, light recreational and residential vehicles	Access restricted
Emergency response	Emergency response vehicles, ground transport	Access restricted, health risk
Winter maintenance and construction	Plowing, grading, sand, culvert de-icing (frozen conditions)	Winter maintenance/construction response (costs, effort) increased
Summer maintenance and construction	Grading, dust abatement, ditch cleaning, brushing, construction (unfrozen conditions)	Summer maintenance/construction response (costs, effort) increased
Safety	Light vehicles, maintenance vehicles	Access restricted, road user safety compromised

APPENDIX B

Table 2 provides a list of suggested climate parameters to consider for inclusion in a resource road risk and vulnerability assessment. The definition of "threshold" values may change depending on the region in which the assessment occurs.

Table 2. List of climate parameters for consideration in an assessment

Climate parameter	Threshold [1]	Relevance to the infrastructure element
Temperature		
Drought conditions	Days with drought code [2] from very high to severe	Wildfire hazard, increased runoff from hydrophobic soils, road dust conditions.
Freeze/thaw cycling	Days when $T_{max} > 0$ °C and $T_{min} < 0$ °C	Laminar ice build-up (glaciation) occurs on watercourses, ditches, and onto roads, preventing function.
Spring thaw	Thawing index; cumulative thawing index > 15-degree days [3]	Weak and thawing road conditions, deep subgrade failures created by heavy trucks.
Rapid snowmelt	1-day snowmelt > X mm	Spring freshet conditions cause runoff and peak stream flow. Culvert and bridge damage or destruction, safety.
Precipitation as rain		
Extremely high rainfall in 24-hour period	1-in-100-year wettest 1-day precipitation	Extremely high runoff. Culvert and bridge damage or destruction, road surface damage or deterioration, safety.
High rainfall in 24-hour period	1-in-20-year wettest 1-day precipitation	High runoff. Culvert and bridge damage or destruction, road surface damage or deterioration, safety. Impacts to smaller basins.
Sustained rainfall	Annual maximum consecutive 5-day precipitation	High runoff. Culvert and bridge damage or destruction, road surface damage or deterioration, safety. Impacts to larger basins and watercourses.
Antecedent rain followed by significant rain event	14-day antecedent rainfall > X mm followed by 1-day rainfall > 1-in-20-year 1-day rainfall	High runoff and saturated soils. Impacts to cut/fill slopes, landslides. Culvert and bridge damage or destruction, road surface damage or deterioration, safety.
Rain on snow	Days per year with 2-day rain > X mm and snow pack > X cm deep	Increased runoff and peak stream flow.
Precipitation as snow		

Snow frequency	Days with > X cm of precipitation as snow (T_{avg} < 1 °C)	Snow plowing results in increased risk to damage of infrastructure.

1. The definition of "threshold" may change depending on the region studied.

2. Drought code is a numeric rating of the dryness of deep organic soil horizons and is a component of the Canadian Forest Fire Weather Index System. It is evaluated using the factor of temperature, with a daily rating of ≥ 300 indicating a very high to severe drought.

3. Spring thaw is modelled using the cumulative thawing index and is used as a threshold to initiate spring load restrictions in various jurisdictions in North America. A typical cumulative thawing index value of 15 degree-days is chosen to initiate the spring load restriction period shortly before road structures become vulnerable to vehicle damage.

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