PROFESSIONAL PRACTICE GUIDELINES

CIVIL AND TRANSPORTATION INFRASTRUCTURE

DEVELOPING CLIMATE CHANGE-RESILIENT DESIGNS FOR HIGHWAY INFRASTRUCTURE IN BRITISH COLUMBIA

VERSION 2.0
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ENGINEERS & GEOSCIENTISTS
BRITISH COLUMBIA

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PREFACE

These *Professional Practice Guidelines – Developing Climate Change-Resilient Designs for Highway Infrastructure in British Columbia* were developed by Engineers and Geoscientists British Columbia (the Association) to guide professional practice related to resilience, reliability, and sustainability of provincial highway assets under changing climate conditions.

These guidelines, which are modelled on the Engineers Canada *Public Guideline: Principles of Climate Adaptation and Mitigation for Engineers* (Engineers Canada 2018), echo and elaborate on the British Columbia (BC) Ministry of Transportation and Infrastructure (BCMoTI) Technical Circular T-04/19, titled Resilient Infrastructure Engineering Design – Adaptation to the Impacts of Climate Change and Weather Extremes (BCMoTI 2019) (Appendix A). These guidelines further complement the Association's *Professional Practice Guidelines – Legislated Flood Assessment Guidelines in a Changing Climate in BC* (Engineers and Geoscientists BC 2018a). The application of these guidelines is specific to Highway Infrastructure owned by the BCMoTI.

Specific factors addressed in these guidelines include how extreme weather events are considered and incorporated into infrastructure design in projects. Examples provided in Section 7.0 Appendices demonstrate the use of climate projections along with engineering judgment in decision-making to promote climate change resilience.

These guidelines were first published in 2016; this current version was revised in 2020 to include the following:

- The updated BCMoTI Design Criteria Sheet for Climate Change Resilience from Technical-Circular T-04/19, which now includes the adaptation cost estimate for BCMoTI Highway Infrastructure projects (Appendix A.1).
- The BCMoTI Design Criteria Sheet, the Climate Change-Resilient Design Report (which can be included along with the Design Criteria Sheet as Explanatory Notes/Discussion), and the Climate Change Risk Assessment Assurance Statement, which are to be used together, have been combined into a single appendix (Appendix A).
- Descriptions of design strategies have been added, such as for the Observational Method and Low-or-No-Regret Strategies outlined in the American Society of Civil Engineers Manual of Practice No. 140 (Section 3.0: Guidelines for Professional Practice).

The Association provides various practice resources to its registrants to assist them in meeting their professional and ethical obligations under the *Engineers and Geoscientists Act*. Among them are professional practice guidelines, which establish the standard of practice for specific professional activities.

These guidelines are not, in and of themselves, prescriptive design requirements, nor do they supersede provisions specified by local governments and other approving bodies. Rather, these guidelines establish a common level of expectation for Clients, statutory decisionmakers, and Engineering/Geoscience Professionals who are addressing climate change and extreme weather events for BCMoTI highway designs. Where relevant, Engineering/Geoscience Professionals are reminded to confirm the adequacy of their liability insurance coverage when carrying out such work.

These guidelines outline the appropriate standard of practice to be followed at the time they were prepared. However, this is a living document that is to be revised and updated as required in the future, to reflect the developing state of practice.

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ABBREVIATIONS

ABBREVIATION	TERM
ACEC	Association of Consulting Engineering Companies
ACEC-BC	Association of Consulting Engineering Companies British Columbia
BC	British Columbia
BCMoTI	British Columbia Ministry of Transportation and Infrastructure
CPE	Coordinating Professional Engineer
EOR	Engineer of Record
FHWA	[US Department of Transportation] Federal Highway Administration
GCM	Global Climate Model
GHG	Greenhouse Gas
QBS	Qualifications-Based Selection
QP	Qualified Professional
PCIC	Pacific Climate Impacts Consortium
PIEVC	Public Infrastructure Engineering Vulnerability Committee
RCP	Representative Concentration Pathway
SRES	Special Report on Emissions Scenarios
VAST	Vulnerability Assessment Scoring Tool

DEFINED TERMS

The following definitions are specific to these guidelines. These words and terms are capitalized throughout the document.

TERM	DEFINITION
Act	*Engineers and Geoscientists Act* [RSBC 1996], Chapter 116.
Adaptation Measure(s)	Actions that reduce the Vulnerability of Highway Infrastructure to the impacts of climate change by reducing the likelihood and/or consequences of failure. These may also include other infrastructure designed to reduce or deflect loads on the primary infrastructure, policies or infrastructure designed to reduce the consequences of failure, increased monitoring, and increased or different maintenance procedures.
Agreement	A formal written or verbal contract or terms of engagement between the Client and the Engineer of Record, or his or her company, for carrying out Climate Change-Resilient Design of Highway Infrastructure. This may also refer to a formal written or verbal contract or terms of engagement between the Qualified Professional or their company and the Engineer of Record or the Client, for conducting a Climate Change Risk Assessment of new or existing Highway Infrastructure.
Association	The Association of Professional Engineers and Geoscientists of the Province of British Columbia, also operating as Engineers and Geoscientists BC.
Assurance Statement	See the definition for Climate Change Risk Assessment Assurance Statement.
BCMoTI Design Criteria Sheet for Climate Change Resilience (BCMoTI Design Criteria Sheet)	The form that engineers working on Highway Infrastructure design projects under the ownership of the BCMoTI are required to complete. The BCMoTI Design Criteria Sheet documents how engineers used their engineering judgment to incorporate consideration of climate change into the appropriate design components of the Highway Infrastructure. The form is completed by the Engineering Professional overseeing the design of the Highway Infrastructure, who is referred to in these guidelines as the Engineer of Record or, for large projects with multiple Engineers of Record, the Coordinating Professional Engineer.
Bylaws	The Bylaws of the Association made under the *Act*.
Client	Typically, the Client is the BCMoTI, who is also the Owner, or a third party contracted to maintain or design the Highway Infrastructure on behalf of the BCMoTI. The individual or company working on a BCMoTI project engages an Engineer of Record to carry out Resilient Design of new or existing Highway Infrastructure. In some cases, the Client may also engage a Qualified Professional to conduct a Climate Change Risk Assessment.

TERM	DEFINITION
Climate Change Information Portal	An online information portal developed by the Association that provides access to climate change adaptation tools and resources to help Engineering Professionals incorporate considerations of climate change into their practice (egbc.ca/climateportal). The information accessed through this portal complements the guidance provided in these guidelines.
Climate Change Resilience	The end result of facilitating the modification, renewal, or renovation of a particular piece of infrastructure, such that its ability to recover from a climate impact is achieved through resistance to failure, swiftness with which functionality is re-established, and reliability of service. Climate Change Resilience is often achieved by using Flexible Design strategies, the goal of which is to avoid committing to a specific course of action, or fully building for future conditions in the present, so as not to unreasonably limit options available in the future to address changing conditions. Examples are securing sufficient right-of-way to allow for future dike raising when necessary, or increasing the size of a culvert so that established design criteria are met during any future extreme-weather events. As some infrastructure may inevitably require periodic renewal or replacement of components, Climate Change Resilience can be relatively easily included as a measure to address climate change for these projects.
Climate Change Risk Assessment (Risk Assessment)	An assessment that involves investigations to determine the risk to the Highway Infrastructure under consideration due to climate change, supported with an appropriate level of analysis and professional engineering and professional geoscience interpretation. The Climate Change Risk Assessment is conducted by a Qualified Professional; however, it may also be conducted by an Engineer of Record with the appropriate expertise. The Public Infrastructure Engineering Vulnerability Committee (PIEVC) Engineering Protocol is a risk assessment method that has been successfully applied to a wide range of public infrastructure projects in Canada and internationally (PIEVC 2020). The ISO 31000 Risk Management standard may be used in the absence of a methodology that follows the PIEVC Engineering Protocol.
Climate Change Risk Assessment Assurance Statement (Assurance Statement)	A statement signed and sealed by a Qualified Professional or the Engineer of Record that provides assurance that these guidelines were applied when completing the Climate Change Risk Assessment (see Appendix A). A Qualified Professional or the Engineer of Record prepares the Assurance Statement and provides it to the Owner.
Climate Risk	The level of a negative impact due to a change in climate. Risk is a function of the likelihood of the climate event and the severity of its consequence. In the Climate Change Risk Assessment, risk is a measure of the level of Vulnerability of the infrastructure to the effects of climate change.
Climate Risk Tolerance	The level of climate change-related risk that the Owner is willing to accept in consideration of a given Highway Infrastructure. It typically depends on the functions and design life of the infrastructure. The PIEVC Engineering Protocol directs the practitioner to confirm the infrastructure Owner's risk tolerance thresholds prior to conducting the Climate Change Risk Assessment. The PIEVC Engineering Protocol suggests high, medium, and low risk thresholds.

TERM	DEFINITION
Climate Specialist	A specialist who studies long-term weather patterns and the processes that cause them. Climate Specialists use long-term meteorological data to study trends in weather patterns, understand their causes, and make predictions. In the context of these guidelines, a Climate Specialist is a professional who, through their expertise and qualifications, assists the Qualified Professional in conducting the Climate Change Risk Assessment, by providing projections of future climate for the region under consideration. A Climate Specialist may also assist the Qualified Professional in understanding what climate parameters need to be considered, by defining climate thresholds for Highway Infrastructure failure and identifying some of the likely impacts of future climate conditions on the Highway Infrastructure under consideration.
Coordinating Professional Engineer (CPE)	An Engineering Professional who is responsible for coordinating the design of a large project, and for overseeing multiple Engineers of Record who are responsible for different aspects of the project.
Engineering/Geoscience Professional(s)	Professional engineers, professional geoscientists, and licensees, who are registered or licensed by the Association and entitled under the *Act* to engage in the practice of professional engineering or professional geoscience in British Columbia. In relation to Highway Infrastructure design: • an Engineering Professional is typically registered in the disciplines of civil (geotechnical, structural, hydrotechnical), mechanical, or electrical engineering, or other disciplines with scopes of practice that contribute to infrastructure design; and • a Geoscience Professional is typically registered in the disciplines of geology or environmental geoscience, or other disciplines with scopes of practice that contribute to infrastructure design.
Engineers and Geoscientists BC	The business name for the Association.
Engineer of Record (EOR)	An Engineering Professional within a design firm who is responsible for design of specific portions of a project (e.g., geotechnical, hydrotechnical, structural, or civil) and assumes professional responsibility for that portion. An Engineer of Record with the appropriate expertise may also act in the capacity of the Qualified Professional and take responsibility for the Climate Change Risk Assessment.
Flexible Design	Highway Infrastructure with Flexible Design has the capacity for components of the design to be changed in the future. Flexible Design may include redundant systems or the ability for the size or functions of design components to be changed in the future. (The term “adaptive design” is synonymous with “Flexible Design.”)
Highway Infrastructure	Infrastructure under the ownership of the BCMoTI. Examples of Highway Infrastructure include, but are not limited to bridges, interchanges, junctions, tunnels, and structures that cross streams, pavements, embankments, ditches, engineering stabilization works, retaining walls, pavements, drainage appliances, and roads.

TERM	DEFINITION
Highway Infrastructure Climate Change-Resilient Design Report	A document that includes the details of the Screening-Level Risk Assessment, Climate Change Risk Assessment, engineering analysis, development of climate change-resilient design criteria, and conclusions and recommendations provided by the Qualified Professional with regard to designing for climate change adaptation. The Highway Infrastructure Climate Change-Resilient Design Report must be provided to the Owner in conjunction with the Climate Change Risk Assessment Assurance Statement (see Appendix A).
Low-or-No-Regret Strategies	Strategies that offer co-benefits under a range of climate change scenarios in the present, and lay the foundation for addressing projected changes in the future (IPCC 2012).
Mitigation	Measures that reduce the emissions of greenhouse gases that drive climate change, which include, but are not limited to, use of renewable energy, improved energy efficiency, reduced energy use, or reductions in embedded energy in materials or products.
Observational Method	A continuous, managed, integrated, robust, on-the-ground engineering process of design, construction control, monitoring, and review that enables previously defined modifications to be incorporated during or after construction, as appropriate. The objective is to achieve greater overall economy without compromising safety (ASCE 2018).
Owner	The BC Ministry of Transportation and Infrastructure. For most Highway Infrastructure projects, the Owner is also the Client (see definition of Client).
Qualified Professional (QP)	An Engineering/Geoscience Professional with the appropriate knowledge and experience to carry out a Climate Change Risk Assessment, . The Qualified Professional should have knowledge of climate science as it relates to the practice of professional engineering and geoscience, in order to be able to carry out appropriately comprehensive Climate Change Risk Assessments. This knowledge should include familiarity with the climate models, tools, and resources appropriate for the project, and the ability to Implement design changes in consideration of the Climate Change Risk Assessment. The Qualified Professional is not expected to have competencies similar to those of a Climate Specialist, but should understand what information must be obtained from a Climate Specialist, in order to carry out a Climate Change Risk Assessment when required. If the Engineer of Record has the necessary experience, the Engineer of Record may fulfill the role of the Qualified Professional and conduct the Climate Change Risk Assessment.
Representative Concentration Pathway (RCP)	Defines a specific emissions trajectory and subsequent radiative forcing (a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the earth-atmosphere system, measured in watts per square meter). As defined in the Fifth Assessment Report from the Intergovernmental Panel on Climate Change (2014), there are four RCPs (RCP 2.6, RCP 4.5, RCP 6, and RCP 8.5).
Resilient Design	The process of incorporating measures into the design of Highway Infrastructure components that address potential negative impacts of climate change, and the measures to recover from those impacts over the full lifespan of the infrastructure components.
Risk Assessment	See the definition for Climate Change Risk Assessment.

TERM	DEFINITION
Robust Design	An approach that affords Highway Infrastructure the ability to reasonably withstand future climate and weather extremes across a range of future scenarios. The decision to develop and implement a Robust Design will be communicated by BCMoTI and may be due to one or more factors: low incremental cost to increase climate resilience compared to a high cost of incremental upgrades; low owner Risk Tolerance; political or societal influence; and/or limited post-construction opportunities to implement additional Adaptation Measures.
Screening-Level Risk Assessment	The first step in a Climate Change Risk Assessment conducted to help the Qualified Professional determine if a more comprehensive Climate Change Risk Assessment is required. One possible result of the Screening-Level Risk Assessment is the determination that no further work is required at the time—that is, if no Vulnerabilities were found that require more detailed assessment. It follows the same procedure as a comprehensive Climate Change Risk Assessment; the only difference between the two is the level of effort expended.
Status-Quo Design	Recognizes that implementing no explicit Adaptation Measures is a valid response, provided the Qualified Professional documents the reason or reasons for this decision. Examples of situations where status quo may be a valid design method are when the Climate Change Risk Assessment shows that the infrastructure is at no risk or low risk due to climate change, or when the service life of the infrastructure is very short and plans are made to reconsider Adaptation Measures when the infrastructure is replaced.
Uncertainty	Generally refers to all of the factors that affect how well the climate data and related information selected for assessment and design will ultimately reflect reality. Climate Specialists also use the term Uncertainty, but with a different and more specific definition (see Section 3.0). These guidelines use the terms “range of values” or “range of potential values” when referring to Uncertainty associated with climate projections. An antonym of Uncertainty is “confidence,” and within the context of these guidelines, the Qualified Professional or the Engineer of Record is looking for confidence that the values used adequately reflect the real-world conditions to which the infrastructure will be exposed, and under which it is designed to function. The less confidence (more Uncertainty) that the Qualified Professional or the Engineer of Record has in the available information, the greater the perceived risk. Greater risk demands more resilient designs.
Vulnerability	The inability of Highway Infrastructure to withstand negative effects and benefit from any positive effects of changes in climate. Vulnerability is a function of the magnitude of the changes in the climate, the sensitivity of the infrastructure to those changes, and the adaptive capacity of the infrastructure. Highway Infrastructure Vulnerabilities are determined and addressed through the Climate Change Risk Assessment.

VERSION HISTORY

VERSION NUMBER	PUBLISHED DATE	DESCRIPTION OF CHANGES
2.0	July 9, 2020	This major revision includes the following changes: • The latest BCMoTI Technical Circular T-04/19, which includes the adaptation cost estimate in the BCMoTI Design Criteria Sheet for Highway Infrastructure projects, has been incorporated. • The Design Criteria Sheet for Climate Resilience, Climate Resilience Design Report, and Climate Change Risk Assessment Assurance Statement, which are to be used together, have been combined into a single appendix, Appendix A. • Section 3.0: Guidelines for Professional Practice now references design strategies outlined in the American Society of Civil Engineers Manual of Practice No. 140. • Minor editorial changes were made to align the content with the current editorial style and brand of Engineers and Geoscientists BC.
1.0	December 2016	Initial version.

1.0 INTRODUCTION

Engineers and Geoscientists British Columbia (the Association) is the regulatory and licensing body for the engineering and geoscience professions in British Columbia (BC). To protect the public, the Association establishes, maintains, and enforces standards for the qualifications and practice of its registrants.

The Association provides various practice resources to registrants to assist them in meeting their professional and ethical obligations under the *Engineers and Geoscientists Act* (the *Act*). Among them are professional practice guidelines, which establish the standard of practice for specific professional activities. The Association works with experts in their respective fields to develop professional practice guidelines where additional guidance is beneficial or required.

In light of strong evidence of climate change, the Association released a Climate Change Position Paper on evolving responsibilities for engineers and geoscientists (Engineers and Geoscientists BC 2014) that includes the following statements:

A. Engineers and Geoscientists BC recognizes that the climate is changing and commits to raising awareness about the potential impacts of the changing climate as they relate to professional engineering and geoscience practice, and to provide information and assistance to Engineers and Geoscientists BC registrants in managing implications for their own professional practice.

B. Engineers and Geoscientists BC registrants (professional engineers, professional geoscientists, provisional members, licensees, limited licensees, engineers-in-training and geoscientists-in-training) are expected to keep themselves informed about the changing climate, and consider potential impacts on their professional activities.

These guidelines aim to provide a structured approach to decision making and record keeping, enabling Clients, stakeholders, and various levels of government to partake in the protection of public safety and the environment; specifically, to assist Engineering/Geoscience Professionals to incorporate impacts of climate change and extreme weather factors in BC Ministry of Transportation and Infrastructure (BCMoTI) Highway Infrastructure designs, while meeting an established standard of practice. In addition, the Association's Climate Change Information Portal was developed to provide an overview of climate change for registrants (see Appendix C). These tools and resources help illustrate incorporating climate adaptation in engineering designs.

These guidelines were prepared in consultation with a steering committee comprising members of multiple organizations and representatives from the fields of engineering, geoscience, and climate change, including the Association of Consulting Engineering Companies (ACEC) Subcommittee for Engineering Adaptation for Climate Change (BC Chapter), the Engineers and Geoscientists BC Climate Change Advisory Group, Engineers Canada, practising consulting engineers, the Pacific Climate Impacts Consortium (PCIC), Environment and Climate Change Canada, and the BCMoTI. (See Appendix D: List of Contributors.)

These guidelines outline the appropriate standard of practice to be followed at the time they were prepared. However, this is a living document that is to be revised and updated as required in the future, to reflect the developing state of practice and the evolution of climate science and the tools and resources for climate adaptation.

1.1 PURPOSE OF THESE GUIDELINES

This document provides guidance on professional practice for Engineering/Geoscience Professionals who carry out a range of professional activities related to Climate Change-Resilient Design for Highway Infrastructure owned by the BCMoTI. This guidance also applies to a Qualified Professional (QP) who completes a Climate Change Risk Assessment (defined in this document as simply "Risk Assessment") for these Highway Infrastructure projects.

Following are the specific objectives of these guidelines:

1. Describe the standard of practice that Engineering/Geoscience Professionals should follow when providing professional services related to these professional activities.
2. Specify the tasks and/or services that Engineering/Geoscience Professionals should complete to meet the appropriate standard of practice and fulfill their professional obligations under the *Act*. These obligations include the Engineering/Geoscience Professional's primary duty to protect the safety, health, and welfare of the public and the environment.
3. Describe the roles and responsibilities of the various participants/stakeholders involved in these professional activities. The document assists in delineating the roles and responsibilities of the various participants/stakeholders, which may include the Engineer of Record (EOR), Coordinating Professional Engineer (CPE), QP, Owner, and contractors.
4. Define the skill sets that are consistent with the training and experience required to carry out these professional activities.
5. Provide guidance on the use of assurance documents, so the appropriate considerations have been addressed (both regulatory and technical) for the specific professional activities that were carried out.
6. Provide guidance on how to meet the quality management requirements under the *Act* and Bylaws when carrying out the professional activities identified in these professional practice guidelines.

1.2 ROLE OF ENGINEERS AND GEOSCIENTISTS BC

These guidelines were prepared by subject matter experts and reviewed at various stages by a formal review group. The final draft of the guidelines underwent a final consultation process with various committees and divisions of the Association. These guidelines and the current revision were approved by the Association's Council and, prior to publication, underwent final legal and editorial reviews. These guidelines form part of Engineers and Geoscientists BC's ongoing commitment to maintaining the quality of professional services that Engineering/Geoscience Professionals provide to their Clients and the public.

An Engineering/Geoscience Professional must exercise professional judgment when providing professional services; as such, application of these guidelines will vary depending on the circumstances.

The Association supports the principle that appropriate financial, professional, and technical resources should be provided (i.e., by the client and/or the employer) to support Engineering/Geoscience Professionals who are responsible for carrying out professional activities, so they can comply with the standard of practice provided in these guidelines. These guidelines may be used to assist in the level of service and terms of reference of an Agreement between an Engineering/Geoscience Professional and a Client.

These guidelines are intended to assist Engineering/Geoscience Professionals in fulfilling their professional obligations, especially regarding the first principle of the Association's Code of Ethics, which is to "hold paramount the safety, health and welfare of the public, protection of the environment and promote health and safety in the workplace." Failure to meet the intent of these guidelines could be evidence of unprofessional conduct and lead to disciplinary proceedings by the Association.

The Association supports the development of common standards of practice in engineering and geoscience across Canada. This includes carrying out Risk Assessments and preparing Highway Infrastructure Climate Change-Resilient Design Reports. Therefore, the Association encourages other engineering and geoscience regulators in Canada to make use of these guidelines in their jurisdictions, with revisions where considered appropriate.

1.3 INTRODUCTION OF TERMS

See the Defined Terms section at the front of the document for a full list of definitions specific to these guidelines.

1.4 SCOPE AND OVERVIEW OF THESE GUIDELINES

These guidelines establish the standard of practice for conducting Risk Assessments and for incorporating Climate Change Resilience into the design of new or retrofit Highway Infrastructure that is under the ownership of the BCMoTI. Although not included in the scope of these guidelines, design professionals also are also expected to consider design strategies that reduce greenhouse gas (GHG) emissions on all BCMoTI projects, such as selecting construction materials and design strategies with the least carbon emissions in consideration of the full design life of the infrastructure.

1.4.1 PROCESS AND OUTCOMES

The detailed guidance, processes, and outcomes provided in these guidelines support the directive set out in the BCMoTI Technical Circular T-04/19 (BCMoTI 2019), which requires reasonable consideration of climate change and extreme weather events appropriate to the scale of the project.

The BCMoTI Technical Circular T-04/19 also requires that a Highway Infrastructure Climate Change-Resilient Design Report including the following information be prepared for each Risk Assessment:

- Details and results of the Screening-Level Risk Assessment
- Details and results of the Climate Change Risk Assessment (if applicable)
- Details of the infrastructure component and climate parameter interactions that were considered, and the risks that were identified, as well as sources of climate data used in the assessment
- How changes to design criteria were developed, as summarized in the BCMoTI Design Criteria Sheet for Climate Change Resilience
- Discussion of adaptation to climate change, considering any changes to design criteria, and including any recommendations for operations and maintenance of the infrastructure

The deliverables for BCMoTI Highway Infrastructure design projects must include, at minimum, a Highway Infrastructure Climate Change-Resilient Design Report, a Climate Change Risk Assessment Assurance Statement (to provide assurance that the appropriate standard of practice was followed for the Climate Change Risk Assessment), and a BCMoTI Design Criteria Sheet for Climate Change Resilience.

Major steps in the design process include the following:

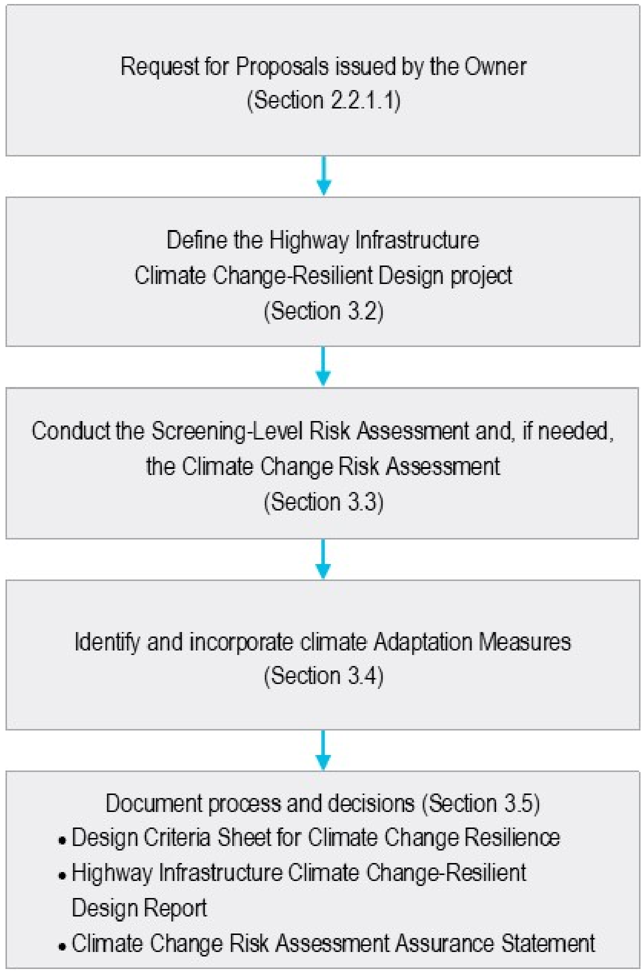

Figure 1: Summary Process for Climate Change-Resilient Design of Highway Infrastructure

These guidelines contain the following sections:

- Section 1.0 Introduction
  - Introduces and identifies the need for and purpose of these guidelines, clarifies the role of the Association, introduces defined terms, and describes the applicability of these guidelines
- Section 2.0 Roles and Responsibilities
  - Outlines the roles and responsibilities of Engineering/Geoscience Professionals, QPs, Climate Specialists, Highway Infrastructure Owners, and other project participants
- Section 3.0 Guidelines for Professional Practice
  - Summarizes the professional practice adaptation strategies and co-benefits that complement or directly support other related climate initiatives, such as efforts to improve disaster preparedness and improve resiliency throughout the lifespan of the Highway Infrastructure
- Section 4.0 Quality Management in Professional Practice
  - Provides information on quality management requirements, and the responsibilities of Engineering/Geoscience Professionals to establish and maintain documented quality management processes

- **Section 5.0 Professional Registration and Education, Training & Experience**
  - Explains the registration, education, training, and experience requirements for Engineering/Geoscience Professionals who engage in the professional activities described in these guidelines
- **Section 6.0 References and Related Documents**
  - Provides references that correspond to in-text citations, as well as related information of value to users of these guidelines
- **Section 7.0 Appendices**
  - Includes the following information:
    - Appendix A: The BCMoTI Design Criteria Sheet for Climate Change Resilience and the Climate Change Risk Assessment Assurance Statement
    - Appendix B: Adaptation Examples from Practising Professionals
    - Appendix C: Overview of Climate Change Tools and Resources for Adaptation
    - Appendix D: List of Contributors

1.5 APPLICABILITY OF THESE GUIDELINES

These guidelines provide guidance on professional practice for Engineering/Geoscience Professionals who carry out Climate Change-Resilient Designs for Highway Infrastructure in British Columbia. These guidelines do not to provide step-by-step instructions for how to carry out these activities; rather, these guidelines outline considerations to be aware of when carrying out these activities.

An Engineering/Geoscience Professional's decision not to follow one or more aspects of these guidelines does not necessarily indicate a failure to meet his or her professional obligations. Such judgments and decisions depend upon weighing facts and circumstances to determine whether other reasonable and prudent Engineering/Geoscience Professionals, in similar situations, could have conducted themselves similarly.

These guidelines do not replace or supersede any guidelines or regulatory requirements provided by the federal, provincial, or local government, or another approving authority, but the various guidelines may be used in conjunction with each other. These guidelines reference, but do not replace, current legislation, regulations, and guidelines.

These guidelines outline the appropriate standard of practice to be followed at the time they were prepared. However, this is a living document that is to be revised and updated as required in the future, to reflect the developing state of practice.

1.6 ACKNOWLEDGEMENTS

This document was reviewed by a group of technical experts, as well as by various committees and divisions of the Association. Authorship and review of these guidelines does not necessarily indicate the individuals and/or their employers endorse all the content in these guidelines.

The Association thanks the authors and reviewers of the original document, as well as the author and reviewers of this revision, for their time and effort in sharing their knowledge and experience. The authors thank the reviewers for their constructive suggestions. Engineers and Geoscientists BC would also like to thank the BCMoTI for providing funding and technical support for the preparation and revision of these guidelines.

The full list of contributors appears in Appendix D.

1.7 UPDATES TO THESE GUIDELINES

These guidelines outline the appropriate standard of practice to be followed at the time they were prepared. However, this is a living document that is to be revised and updated as required in the future, to reflect the developing state of practice.

Climate science as it relates to professional engineering is constantly evolving. The examples of case studies and Highway Infrastructure Climate Change-Resilient Design Reports in Appendix B: Adaptation Examples From Practising Professionals of these guidelines illustrate methods that can be used to incorporate climate change considerations into design.

Feedback received on these guidelines will inform future updates, and users who have successfully applied these guidelines to the design of Highway Infrastructure are encouraged to submit copies of their Highway Infrastructure Climate Change-Resilient Design Reports to the Association.

Submitted case studies and reports may be considered for inclusion in future updates to these guidelines or in the Association's online Climate Change Information Portal (egbc.ca/Practice-Resources/Climate/Climate-Change-Information-Portal).

To submit a report, contact Harshan Radhakrishnan, P.Eng., Engineers and Geoscientists BC Manager, Climate Change and Sustainability Initiatives (email:hrad@egbc.ca).

2.0 ROLES AND RESPONSIBILITIES

2.1 COMMON FORMS OF PROJECT ORGANIZATION

Typically, the Highway Infrastructure Owner is the Client, who establishes an Agreement for professional services with the Engineer of Record (EOR). Within the Agreement, the EOR should ensure the EOR's role and relationship with the Client is clearly defined.

The EOR oversees the project and is responsible for incorporating Climate Change Resilience into the design of Highway Infrastructure. For large projects with multiple EORs, a Coordinating Professional Engineer (CPE) oversees the overall project, ensures Climate Change Resilience is incorporated appropriately into the design of Highway Infrastructure, and fulfills the EOR responsibilities as outlined in this section.

An EOR with the appropriate expertise may also act in the capacity of the Qualified Professional (QP) and take responsibility for the Climate Change Risk Assessment (defined in this document as simply "Risk Assessment"). However, if the EOR is unable to act as the QP, the EOR establishes an Agreement for professional services with a QP who will be responsible for the Risk Assessment. The report detailing the results of the Risk Assessment should be prepared in consultation with the EOR, who will then incorporate the QP's recommendations into the Highway Infrastructure design.

In some cases, the Client may not fully understand or appreciate the level of effort required by the EOR to carry out climate change-resilient design of the Highway Infrastructure. In such a case, the data and previous assessments that are available to the QP for conducting the Risk Assessment may significantly affect the level of engineering analysis carried out by the EOR.

The EOR should review the typical responsibilities listed in this section, to assist in establishing an appropriate Agreement for professional services with the Client, and to inform them of the expectation of appropriate and adequate compensation (Engineers and Geoscientists BC Code of Ethics Principle 5).

2.2 RESPONSIBILITIES

Sections 2.2.1, 2.2.2, and 2.2.3 describe typical responsibilities of the Client, the EOR, and the QP, respectively.

Section 2.2.4 describes how another QP may be engaged to carry out an independent external review of the Climate Change-Resilient Design Report at the Owner's expense.

Figure 2: Roles and Responsibilities of Professionals in Highway Infrastructure Projects below illustrates the project organization and typical responsibilities of the EOR, QP, CPE, and Climate Specialist.

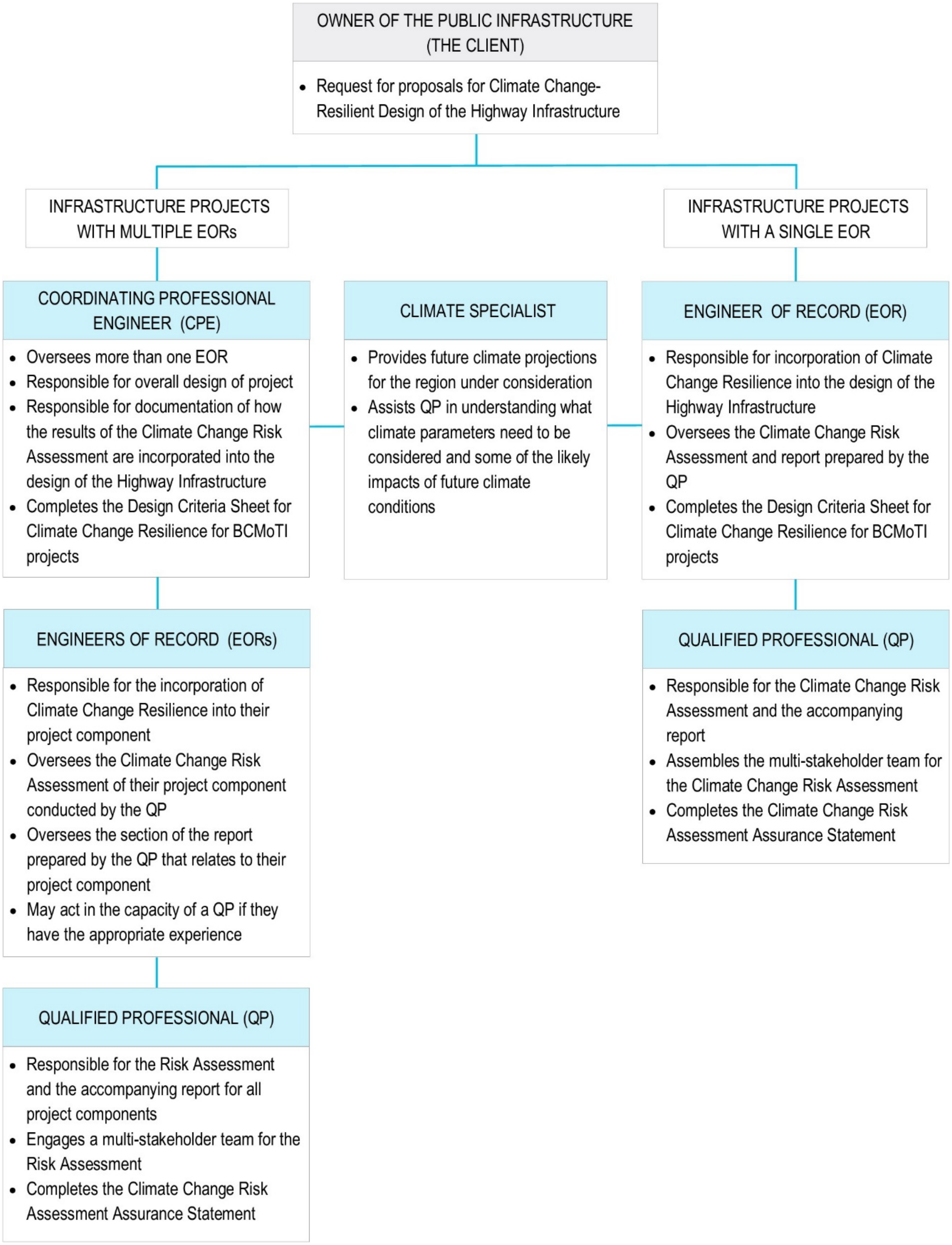

Figure 2: Roles and Responsibilities of Professionals in Highway Infrastructure Projects

NOTES:

Abbreviations: BCMoTI = British Columbia Ministry of Transportation and Infrastructure; CPE = Coordinating Professional Engineer; EOR = Engineer of Record; QP = Qualified Professional

2.2.1 CLIENT OR HIGHWAY INFRASTRUCTURE OWNER

The Client, who may also be the Highway Infrastructure Owner, recommends the climate projection resources for the EOR or QP to use in the Risk Assessment. Alternatively, the EOR recommends resources for the Owner's approval or as part of the EOR's proposal.

These resources may include climate data providers, such as the Pacific Climate Impacts Consortium (PCIC), that can produce appropriate climate projections. Depending on the project, it may be advisable to engage a Climate Specialist with regional experience in climate change projections relevant to the project.

2.2.1.1 Preparing the Request for Proposals

The request for proposals for climate change-resilient design of a Highway Infrastructure project should clearly outline the appropriate level of Risk Assessment required. This section should be based on the Climate Risk Tolerance identified by the Owner (if available), and should reflect the state of knowledge of the design, construction, operation, and maintenance of the Highway Infrastructure, as well as the availability of climate projections, the level of service, and the service life.

2.2.1.2 Procurement of the Engineer of Record

The Client selects the EOR based on qualifications, availability, experience, and local knowledge, using a Qualifications-Based Selection (QBS) process. The recommended best practices for selecting an engineering consultant to act in the capacity of an EOR can be found in the document titled InfraGuide Best Practice – Selecting a Professional Consultant (FCM and NRC 2006). This process identifies the need for a QP to be engaged in the project.

The Association of Consulting Engineering Companies British Columbia (ACEC-BC) has developed an online resource to help municipalities and other Owners implement effective procurement practices. The dedicated website yes2qbs.com (ACEC-BC 2015) brings together QBS-related information in one location and includes guides, templates, and studies that offer a detailed explanations of the QBS process.

2.2.2 ENGINEER OF RECORD

The EOR oversees the project and is responsible for the overall concept, sizing, risk analysis, design, costing, project management, and documentation. The EOR normally receives and approves the Risk Assessment report from the QP and is responsible for documenting and incorporating recommendations into Highway Infrastructure designs. For projects under the ownership of the BCMoTI, the EOR should complete and sign the BCMoTI Design Criteria Sheet for Climate Change Resilience to document the consideration of Climate Change Resilience in each design component.

On large projects, the CPE and/or the EOR are responsible for assembling and overseeing a multi-stakeholder team of individuals with the appropriate qualifications and experience to carry out climate change-resilient design for a Highway Infrastructure project. It is also appropriate for the Client to approve the multi-stakeholder team prepared by the CPE and/or the EOR.

2.2.2.1 Selection of Qualified Professional

An EOR with the appropriate expertise may also act in the capacity of the QP and take responsibility for the Risk Assessment. However, If the EOR is not qualified to act as the QP, the EOR may select a QP who is also an Engineering Professional to be part of the design team, based on the QP's qualifications, availability, and local knowledge.

Once the EOR has selected a QP to conduct the Risk Assessment, the EOR, with assistance from the QP, should complete a written Agreement. The Agreement confirms the scope of work, schedule, and cost estimate for the Risk Assessment, as well as the need and scope of specialty services for external peer review.

The following clause is recommended to be included as part of the Agreement, to address the EOR's obligations regarding potential disclosure issues under

Association's Code of Ethics Principle 1. The EOR may have to convey adverse Risk Assessment findings to parties who may not be directly involved, but who have a compelling need to know. Following is the suggested wording for such a clause:

> *Subject to the following, the Qualified Professional will keep confidential all information, including documents, correspondence, reports, and opinions, unless disclosure is authorized in writing by the Client. However, in keeping with Engineers and Geoscientists BC's Code of Ethics, if the Qualified Professional discovers or determines that there is a material risk to the environment or the safety, health, and welfare of the public or worker safety, they shall notify the Client as soon as practical of this information and the need that it be disclosed to the appropriate parties. If the Client does not take the necessary steps to notify the appropriate parties in a reasonable amount of time, the EOR shall have the right to disclose that information in order to fulfill their ethical duties and the Client hereby agrees to that disclosure.*

The QP is obligated under the Association's Code of Ethics Principle 8 to "present clearly to employers and Clients the possible consequences if professional decisions or judgments are overruled or disregarded." In particular, these guidelines require QPs to convey all potential risks and consequences associated with not implementing the recommended climate change Adaptation Measures.

2.2.3 QUALIFIED PROFESSIONAL

It is the responsibility of the EOR and, as applicable, the QP to assemble a multi-stakeholder team of individuals with the appropriate qualifications and experience in relevant disciplines to carry out a Risk Assessment. It is the responsibility of the QP to provide recommended Adaptation Measures and Assurance Statement(s) to the EOR and the Client. The QP assumes full responsibility for all work delegated in accordance with the *Act*.

On projects where past climate data and regional climate projections are readily available and endorsed by the Owner, the QP may independently conduct a Risk Assessment under the following circumstances:

- The QP has developed proficiency in these kinds of Risk Assessments, which can include working on projects in the same geographic area
- The QP has worked with multi-stakeholder teams on Risk Assessments, while ensuring that the assessment is compatible with other relevant work being completed by the Owner, which can include related infrastructure
- The QP has access to appropriate regional climate projections

2.2.4 EXTERNAL REVIEW OF A HIGHWAY INFRASTRUCTURE CLIMATE CHANGE-RESILIENT DESIGN REPORT

If the Owner requires additional external review of the Highway Infrastructure Climate Change-Resilient Design Report, another suitably QP may be engaged to carry out an independent external review at the Owner's expense.

3.0 GUIDELINES FOR PROFESSIONAL PRACTICE

This section of these guidelines establishes the standard of practice that is expected of Engineering/Geoscience Professionals who are responsible for incorporating Climate Change Resilience into Highway Infrastructure designs.

Historical climate records are considered to be a reflection of "reality" and, through statistical analysis, they assist in the development of design values to address climate Uncertainty. From an engineering perspective, the full ensemble of global climate models (GCMs) encompass greater Uncertainty in future climate projections than those in historical records. The fact that climate models are being refined, especially with respect to projecting extreme values, creates a perceived increase in risk, which must be acknowledged and managed to ensure resilience over the full design life of the infrastructure. Thus, it becomes imperative to include a Climate Change Risk Assessment (defined in this document as simply "Risk Assessment") in the Highway Infrastructure design process.

The methods to address a wide range of Uncertainty in infrastructure design are outlined in the American Society of Civil Engineers (ASCE) Manual of Practice No. 140 titled Climate-Resilient Infrastructure: Adaptive Design and Risk Management (ASCE 2018).

Engineers of Record (EORs) should develop a new paradigm for engineering practice in a world in which climate change is occurring but cannot be projected with a high degree of certainty. When it is not possible to fully define and estimate the risks or potential costs, or to reduce the Uncertainty in the time frame in which action should be taken, a first step is to use low-regret adaptive strategies to make a project more resilient to future climate and weather extremes.

Engineering/Geoscience Professionals working on BCMoTI projects are expected to consider the design strategies and Risk Assessment methodologies outlined in this section. For BCMoTI projects, the estimated costs of climate adaptation for the components of the project (such as increasing the size of culvert pipes) must be documented.

Note: The adaptation cost estimate is for a present-day "as-designed" configuration; other costs related to phased adaptation should be included in the Explanatory Notes/Discussion section of the BCMoTI Design Criteria Sheet for Climate Change Resilience (Appendix A).

While benefit-cost analyses for highway improvement projects in British Columbia (BC) focus on vehicle-travel–related greenhouse gas (GHG) emissions, design professionals are also expected to consider design strategies that reduce GHG emissions on all BCMoTI projects, such as selecting construction materials and design strategies with the least carbon emissions in consideration of the full design life of the infrastructure.

3.1 OVERVIEW

The Engineer of Record (EOR) or Coordinating Professional Engineer (CPE) (if there are multiple EORs on a project) is responsible for the overall project design, while considering the impacts of climate change and incorporating Adaptation Measures, where appropriate. The Qualified Professional (QP) is responsible for conducting the Risk Assessment and facilitating the development of Adaptation Measures.

3.1.1 LEVEL OF EFFORT AND DETAIL

The level of effort required for a Risk Assessment does not always depend on the scope and scale of the project. It can also depend on the availability of climate data for analysis.

For example, consider the hydrotechnical design of two bridges with similar scope in different geographic locations: one bridge is located in a watershed where the PCIC, or other agencies such as Environment and Climate Change Canada or universities, already provide projected flows, whereas the other bridge is in an area where only projected temperatures and precipitation data are available.

It the latter example, developing a hydrologic model to estimate flows from projected temperature and precipitation would require significant effort. Therefore, the amount of effort required for the two projects would be considered significantly different.

Each Risk Assessment task described in this section includes a statement about how to satisfy the requirement for “minimum level of effort.”

Note: Irrespective of the level of effort applied, the EOR and QP must appropriately assess and address future climate conditions by incorporating Climate Change Resilience into the design of BCMoTI Highway Infrastructure, and by documenting all conditions being considered, including assumptions and limitations.

3.1.2 SUMMARY OF ROLES AND RESPONSIBILITIES

Figure 3 below outlines the roles, responsibilities, and processes for carrying out climate change-resilient design of a Highway Infrastructure project. The flow chart outlines the specific participation of the QP, EOR, and Owner within the project, and has been adapted to work with the BCMoTI Technical Circular T04/19 (Appendix A) and the Public Infrastructure Engineering Vulnerability Committee (PIEVC) Engineering Protocol (PIEVC 2020).

3.2 DEFINE THE PROJECT

Identifying details of the project provides the context for evaluating Climate Risk and incorporating Adaptation Measures into the design.

Key steps include the following:

- Characterize the project location
- List the key infrastructure components
- Identify non-climate design drivers
- Identify general climate parameters that should be considered
- Select the key team members
- Identify key stakeholders
- Define the project time horizons

The following subsections describe each task in detail.

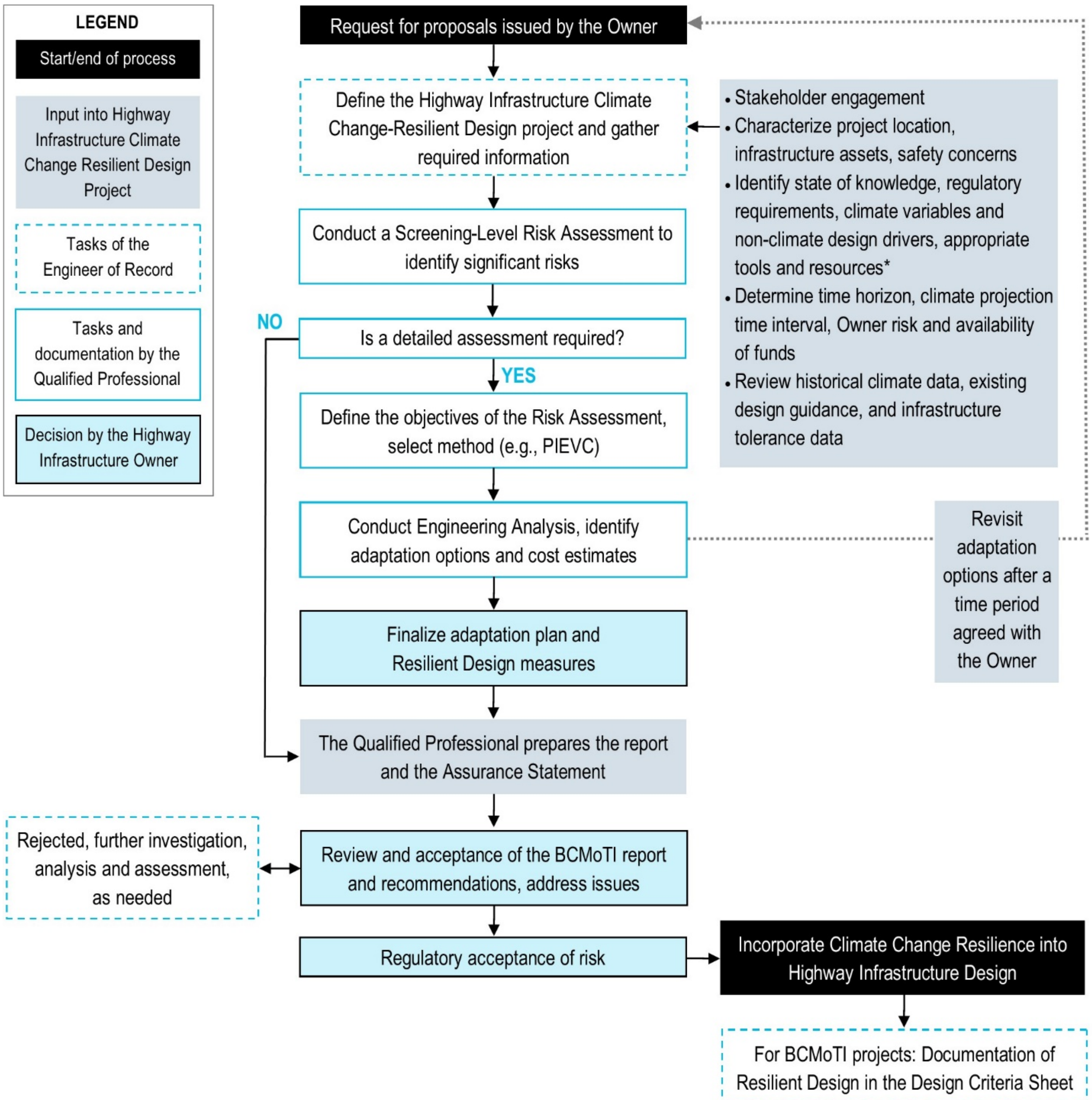

Figure 3: Roles, Responsibilities, and Processes of Carrying out Climate Change-Resilient Design of Highway Infrastructure

* In projects where there is no multi-stakeholder team, no climate data provider, or no guidance from the Owner, the Climate Change Information Portal (Engineers and Geoscientists BC 2019) may be used to identify appropriate tools and resources to support climate change adaptation.

3.2.1 CHARACTERIZE PROJECT LOCATION AND IDENTIFY INFRASTRUCTURE

For the purpose of these guidelines, the term “project location” encompasses an area beyond the project’s extent. Identifying a broadened project area provides context as to how infrastructure, both present and future, are affected by climate change. For example, a road located along the coast may be prone to tidal and storm surges, while a road through a mountain pass may be prone to deep snow buildup. Despite these differences, both could be subject to high stream flows, avalanches, or intense rainfall.

The examples below provide additional context to identify and communicate climate-related issues throughout the design phase. This includes, but is not limited to the following:

- Project limits
- Water bodies, streams, and drainage catchments
- Topographic characteristics: elevation range, slopes, high and low points
- Geographic characteristics: flood plain, alluvial fan, mountain side, narrow valley
- Geologic characteristics: geology, soil types, groundwater
- Populated or developed areas
- Environmental resources: wetlands, habitat, riparian areas
- Other critical infrastructure: power lines, dams, gas or oil facilities
- Local or provincial standards, applicable bylaws, and land-use zoning

It is also useful to list the key infrastructure components to be designed and constructed. Details are not required at this stage of the project but should be sufficient to understand project elements. For example, estimating the quantity and location of various Highway Infrastructure components of a highway project would include the following:

- Roadways: number of lanes, lane separation
- Bridges
- Grades: separated intersections
- Culverts: by relative size (small, medium, large)
- Stormwater detention and/or treatment facilities
- Snow sheds
- Breakwaters
- Retaining walls

Minimum Level of Effort

In this case, the level of effort would be proportional to the scope and scale of the project. If, for example, the project consists of lane widening for a couple of kilometers and includes one stream crossing, only key items would be shown on the location map, such as the extents of the project, the stream, and any other items that might impact the infrastructure because of climate.

3.2.2 IDENTIFY NON-CLIMATE DESIGN DRIVERS

Constructing Highway Infrastructure is a general response to population growth, fostering economic development, delivering goods and services to communities, improving safety, or any combination of these demands. The purpose of identifying these non-climate design drivers is to establish a base design scenario. For example, if the project is to provide increased capacity in response to population growth, then design criteria will adjust accordingly. This base scenario provides the means to evaluate the significance of any potential climate change impacts on the project or design service life.

Consider the broader non-climate design drivers. Increasing capacity to service population growth in areas prone to sea-level rise could influence not only the design of the infrastructure, but the viability of the project itself. Identifying these issues as part of the project definition could be useful when determining what, if any, design changes must be incorporated into the project in order to address risks posed by climate change. These factors, however, are not part of the Risk Assessment.

Minimum Level of Effort

A simple list or short description of these drivers agreed among project stakeholders and, most importantly, with the Owner would fulfill this requirement. The key is to be aware that these drivers exist and will have an impact on the design.

3.2.3 IDENTIFY CLIMATE PARAMETERS

Examples of climate parameters typically used during design of the Highway Infrastructure may include, but are not limited to the following:

- Rainfall: intensity, duration, frequency
- Temperature: maximum, minimum, average degree days
- Snow: daily snowfall, total accumulated depth
- Wind: average speeds, maximum gusts, direction
- Sea level: average level, high tides, storm surges
- Flow: average, maximum, and minimum stream water levels and flows

It is important to recognize that one or more of these climate parameters will directly affect other design values. For example, rainfall, temperature, and snowmelt will all impact stream flow, which is used to size hydraulic components such as culverts and bridges. Also, certain combinations of humidity and temperature form fog and ice, which are hazards to public safety.

The task to identify all pertinent climate parameters, even those that indirectly affect the design, are critical to the safety, resilience, and reliability of Highway Infrastructure. The level of effort for identifying the details of each climate parameter is largely based on the size, scope, and geographic location of the project.

3.2.4 DEFINE PROJECT TEAM AND IDENTIFY STAKEHOLDERS

Each Highway Infrastructure design project is unique, so requires a project team with the appropriate set of specialized skills and knowledge for completing that particular project. Irrespective of project scale, scope, and number of team members and stakeholders, it is essential that all parties involved are aware of potential impacts of climate change and corresponding implications to the design. Having discussions in a facilitated workshop will allow team members to identify the level of effort required to determine the potential impacts of climate change and corresponding implications to the design.

Early in the project, the EOR or CPE should recruit and list the key team members and stakeholders, as well as define their roles.

The following list is an example of potential team members and their general responsibilities; details will vary by project. (See also Section 2.0 Roles and Responsibilities.)

- Owner: project scope definition, financial decisions, risk acceptance
- EOR: overall concept, sizing, risk analysis, design, costing, project management, documentation, overall design responsibility
- QPs or specialty engineers, project managers, and other practitioners (e.g., functional, geotechnical, structural, geoscientists, hydrotechnical, drainage, environmental, coastal, electrical, communications): performance, safety, operations and maintenance, sizing, risk analysis, detailed design (e.g., costing, longevity, documentation)
- Approvals officers: review and approvals, standards enforcement
- Legal and accounting professionals
- Staff who confirm the engagement of public; e.g., community representatives

Likewise, for addressing climate change, key team members should include QPs and specialists with the following expertise:

- Climate projections: May be developed by a climatologist or Climate Specialist on major projects, but on most projects, projections are acquired from third-party, published data (e.g., from the PCIC).

- Risk Assessment: One or more experienced individuals who can provide sound judgment with respect to potential interactions between specific climate parameters and components of the Highway Infrastructure being designed. Depending on the design project, additional team members might include individuals with knowledge and experience in:
  - natural science, hydrology, geology, forestry, biology, environment;
  - operation and maintenance for the infrastructure being assessed;
  - management; and
  - local knowledge and history of previous climatic events.
- Climate adaptation: A QP or group of QPs that develop and recommend design, and advise on operation and maintenance measures to improve the Climate Change Resilience of the proposed infrastructure.
- Risk-based design: A design professional who can account for, and communicate to the Owner and possibly the approvals officers, the various risks associated with projected climate change, and who can complete the design to meet an accepted level of risk.

In special cases, key team members may include individuals with knowledge and experience in one or more of the following fields:

- Public safety
- Social impacts
- Economic impacts
- Politics
- Insurance
- Community issues
- Emergency preparedness and response

These additional team members can be critical to the success of the Highway Infrastructure design project. It is the QP's responsibility to know when the expertise of each of the specialty team members is required, and to engage them accordingly.

Minimum Level of Effort

The project team should include, at a minimum, the Owner, the EOR, and an individual who is reasonably knowledgeable about general climate projections. The team members must have sufficient knowledge and experience to identify and characterize key climate events that could impact the Highway Infrastructure, determine what types of interactions might occur between the climate events and the infrastructure, estimate the likelihood of the interactions occurring, and estimate the corresponding consequences should the interaction occur.

3.2.5 DEFINE ASSESSMENT TIME HORIZON

Highway Infrastructure projects such as bridges have relatively long service lives—typically 50, 75, or even 100 years. Since many climate parameters exhibit trends of increasing or decreasing average annual values, as well as higher and more frequent extremes, it is important to select projected climate data that correspond to the service life of each Highway Infrastructure project.

The range of values projected using different GCMs may also increase with the time horizon. For example, the difference between the highest and lowest average annual temperature generated by the full ensemble of GCMs for the year 2100 is greater than that for the year 2030. Therefore, the combination of infrastructure longevity and plausible range of projected climate parameter values makes it important to identify the expected service life of the components and systems that comprise the proposed Highway Infrastructure. This provides context for developing climate projections, conducting Risk Assessments, and identifying appropriate Adaptation Measures.

Infrastructure with a short service life is usually subject to periodic refurbishment or replacement. This provides an opportunity to re-evaluate corresponding Climate Risks and Adaptation Measures. Risks associated with climate change for such infrastructure may be low because the climate trend has had little time to develop. However, for infrastructure components that are not eligible for replacement or refurbishment before the end of their service lives, the consequences of decisions made during the design process can be significant.

Extreme annual climate values may exhibit greater increases and fluctuations over a short time horizon than average climate values. For the Risk Assessment, the QP should select the most appropriate climate parameter(s) and values relevant to the Highway Infrastructure design.

It is important to recognize that the QP is not expected to make perfect decisions but is expected, "based on professional judgment, to make appropriate decisions within the context of current scientific, economic, and social constraints" (Engineers Canada 2015). Nevertheless, the assumptions and limitations of such decisions should be appropriately documented.

Minimum Level of Effort

At minimum, the project team could assign a single assessment time horizon for the entire project, based on the infrastructure component with the longest service life. Infrastructure elements that have relatively short service lives may be identified and, if appropriate, eliminated from the Risk Assessment.

3.3 CONDUCT THE CLIMATE CHANGE RISK ASSESSMENT

The first component of a Risk Assessment is to identify and evaluate the risks pertinent to the area of interest. The QP should have a reasonable level of competence in Risk Assessment, particularly with respect to deriving and implementing risk controls as outlined in Table 1 below.

Table 1: Suggested Standard of Practice of a Qualified Professional Conducting a Climate Change Risk Assessment

PROJECT DETAILS	PROFESSIONAL CONSIDERATIONS
Project scope	• Identify whether an Owner-defined Climate Risk Tolerance is available; if not, engage with the Owner to establish their Climate Risk Tolerance. • Establish the Owner-defined time horizon for the infrastructure.
Project team (project-dependent)	• Assemble a qualified project team in collaboration with the Owner.
Regional climate projections	• These are normally developed by a Climate Specialist. • A range of Representative Concentration Pathways (RCPs) or equivalent Special Report on Emissions Scenarios (SRES) should be used to generate regional climate projections appropriate to the project. • An ensemble of models should be used to generate regional climate projections. For example, the top three climate models for Western North America, as indicated by the Pacific Climate Impacts Consortium (PCIC), are CNRM-CM5-r1, CanESM2-r1, and ACCESS1-0-r1 (PCIC 2019). • The design should be based on existing codes and standards, but future climate projections for the time horizon identified should be substituted for the climate data. For example, if the code suggests design flows with a return period of 1:200 (Q200), and the climate projections suggest a 25% increase in flows, then the revised design flows should be Q200+25%.
Background information	• Review available background information and collect additional information (see Figure 2) or organize a team to conduct sufficient field work.

PROJECT DETAILS	PROFESSIONAL CONSIDERATIONS
Climate adaptation method	• Explore the following adaptation methods: – Robust Design that makes the infrastructure resilient to a wide range of future climate projections – Flexible Design that includes redundant systems or has the capacity for design components to be changed in the future – Status-Quo Design that recognizes that implementing no explicit Adaptation Measures is a valid response – Observational Method that bases project designs on the most-probable weather or climate conditions, as opposed to the most-unfavorable conditions (ASCE 2018), with plans to address a wide range of Uncertainty in infrastructure design (Patel et al. 2007) – Low-or-No-Regret Strategies that offer co-benefits under a range of climate change scenarios in the present, and lay the foundation for addressing projected changes in the future (IPCC 2012) • Revisit the Owner-approved adaptation options, as needed.
Highway Infrastructure Climate Change-Resilient Design Report	• Convey to the Owner in plain language the climate change risks associated with status-quo/worst-possible emissions scenarios (for example, RCP 8.5), to enable decision-making. • Address the frequency of required reassessment and monitoring (and climate data collection appropriate for the location to inform future design). • For small projects involving only one engineering discipline (e.g., hydrotechnical design of channel training works at an existing bridge), climate change-resilient design may be discussed in a subsection of the main design report and does not have to be a standalone report.
Project documentation	• Record detailed Risk Assessment findings and assumptions. • Communicate results to all stakeholders involved. • Identify the climate model ensemble and its limitations. • Identify the Risk Assessment tool (and version), if applicable. • Complete, sign, and seal the BCMoTI Design Criteria Sheet for Climate Change Resilience and the Climate Change Risk Assessment Assurance Statement.

3.3.1 DEFINE OBJECTIVES

The Risk Assessment should include design objectives with respect to capacity, safety, reliability, durability, longevity, and other elements that contribute to the Climate Risk Tolerance of the Owner.

For example, consider a road that is the only viable route to a given location. The community faces severe hardship if road closures exceed two days. This adds a social objective in the infrastructure components and climate parameters selected for the Risk Assessment.

Minimum Level of Effort

There is little opportunity to reduce effort for this task, except perhaps in the level of documentation detail.

3.3.2 SELECT RISK ASSESSMENT METHOD

Many Risk Assessment methods include guidance for evaluating the risks; at their core, each Climate Change Risk Assessment includes:

- a list of infrastructure components, typically to the subsystem level, that could potentially interact with or be affected by at least one climate parameter;

- a list of climate parameters that are judged to have a negative impact on the infrastructure safety or performance;
- a risk matrix showing the combinations of listed infrastructure components and specific climate parameters, and identifying the combinations where there is potential for the infrastructure component to be negatively impacted by a change in the climate parameter;
- assignment of a numerical likelihood value (score) to each climate parameter, indicating the likelihood that each interaction identified in the matrix will occur, according to an agreed scoring system of typically three, five, or seven levels;
- assignment of a numerical severity/consequence rating (score) to each potential interaction of a climate parameter with an infrastructure component in the matrix, should the interaction occur; and
- a calculation of risk (the product of the severity/consequence rating and likelihood value) for each interaction.

At minimum, Risk Assessments can be more quantitative than the items listed above, which uses a qualitative approach. Many methods aligning with those described in the ISO 31000 Risk Management standard include guidance for evaluating and managing the risks once they have been identified, which can be useful.

Following are commonly used tools to assess Climate Risk for Highway Infrastructure. It is the QP's responsibility to remain informed about the status of available tools and methods to ensure that the most current version is applied.

- PIEVC Engineering Protocol for Climate Change Infrastructure Vulnerability Assessment (PIEVC 2020)
  - Described as a comprehensive screening-level infrastructure Climate Risk/Vulnerability process commonly used for planning and initiating the process and documenting each step.
  - Designed by the PIEVC, the Protocol provides a structured iterative process to complete the assessment, including details such as team composition, how information is gathered and assessed, how results are interpreted, and how the entire process is documented.
  - The Protocol is available at no financial cost for public infrastructure in Canada.
- US Department of Transportation Federal Highway Administration (FHWA) Vulnerability Assessment Scoring Tool (VAST) (FHWA 2019)
  - Described as a spreadsheet tool that guides the user through a quantitative, indicator-based Vulnerability screen.
  - The VAST is free for download and used without further interaction with the FHWA. This ease of access makes the tool attractive, especially for smaller or less-complicated design projects.
  - In larger or complicated design projects, the VAST does lack specific elements that may eventually prove useful (e.g., team development and documentation), compared to what is available in the PIEVC Engineering Protocol.
- Engineers and Geoscientists BC Climate Change Information Portal (Engineers and Geoscientists BC 2019)
  - The climate change adaptation tools and resources listed in this portal aim to support Engineering/Geoscience Professionals who are incorporating a consideration of climate change into their practice.
  - Contains details about the PIEVC Engineering Protocol, the VAST, and other Risk Assessment tools and methods.

Risk Assessment methods and tools were originally developed to assess existing infrastructure, as the physical attributes of infrastructure are well documented. One can determine existing infrastructure's Climate Change Resilience by determining if the load generated by projected climate is less than its capacity. Today, these methods are already in use at the design phase.

The capacity or expected performance of any infrastructure should be determined at the beginning of a Vulnerability assessment; this way, infrastructure with high-risk scores can be resized using projected climate values to reduce risk.

Minimum Level of Effort

At a minimum, a simple table that lists the selected climate events and their effect on specific design components is sufficient, like that which is included in the BCMoTI Design Criteria Sheet for Climate Change Resilience (Appendix A).

3.3.3 SELECT INFRASTRUCTURE COMPONENTS

Infrastructure components may be defined either individually, as groups, or as both, if the situation warrants. For example, the QP may choose to group all roadway culverts as a single component, list each culvert as a single component, or group some culverts into a single component while listing others individually. Similarly, a bridge may be defined as a single infrastructure component or as individual components (e.g., piers, abutments, superstructure, and deck).

Individually listing infrastructure components may yield a more detailed Risk Assessment, but will require extra effort and cost. The EOR should determine an appropriate balance between effort and effectiveness. The PIEVC Engineering Protocol provides case studies illustrating how infrastructure components are defined for similar projects, to assist the EOR in selecting and grouping infrastructure components that are sensitive to climate change (PIEVC_2020).

The questions below can be used to guide the decision-making process, to determine whether to assess a particular infrastructure component individually, as part of groups of components, or not at all.

- Is there a potential interaction between one or more climate parameters and the infrastructure component? If climate change has no obvious impact on the component, then there is no reason to include it in the assessment. However, appropriate documentation of the decision is required as part of the assessment.
- What is the functional life span of the component? Is it likely to be replaced through routine maintenance in a few years, or will it remain in service for decades? Only include the component if it is likely to be in service in the distant future. Where components can be replaced through routine maintenance they can potentially be excluded from the assessment.
- How critical is the component to the overall performance of the project? Would its failure cause significant impacts in terms of performance and/or safety? Is the component easily replaceable or repaired, or would this be costly in terms of money and time?
- Are there many identical or similar components in the project? Is it likely that their response to a specific climate change parameter would also be similar? This is usually a good indicator to assess these components as a group.

The QP should work with team members to create the list of infrastructure components for assessment. By using engineering judgment, the QP determines if components should be assessed individually, as part of groups of components, or as the infrastructure as a whole.

Minimum Level of Effort

At a minimum, it may be adequate to start with the infrastructure as a whole, or with key component groups if the infrastructure is more complex.

For example, if the project is a new or upgraded road that includes no major structures—such as bridges, grade-separated intersections, or snow sheds—then the selected infrastructure could simply be considered a “road structure.” However, if the project does include major structures, the list could be expanded to include primary structure groups; for example, culverts, bridges, or snow sheds.

3.3.4 SELECT AND DEFINE SPECIFIC CLIMATE PARAMETERS

The QP should define design thresholds for the climate parameters, as outlined in Section 3.2.3 Identify Climate Parameters, by adding one or more climate values for parameters that could cause failure of the component or cause damage that would adversely affect its performance or the performance of the infrastructure as a whole. The listing of climate parameters must be clearly documented in the design process for components. Each climate parameter should interact with, or affect the performance or safety of, at least one of the infrastructure components, as described in Section 3.3.3 Select Infrastructure Components. Detailed examples are provided in Appendix B: Adaptation Examples From Practising Professionals, under Section B.6: A Summary of PIEVC Risk Assessments Conducted by the BC Ministry of Transportation and Infrastructure.

QPs may have the knowledge and experience to select and interpret projected climate threshold values; however, if not, then the QP should work with a Climate Specialist to determine the appropriate parameters and corresponding values to include in the Risk Assessment (see Section 3.2.4 Define Project Team and Identify Stakeholders). This is especially important for certain climate parameters (e.g., sub-daily rainfall intensities), as projected values are from annual averages or, at best, daily values. The QP should ensure appropriate documentation of the range of values identified and determine the suitability for the intended purpose.

Engineering specialists may identify secondary climate variables as appropriate to the design process. For example, increased surface temperatures over time may have profound influences on the durability of asphalt mix used for construction. If climate data and projections for a climate parameter are not available, Climate Specialists working closely with engineers may jointly recommend a climate parameter, or an indicator may be used as a proxy to determine a probability of exceedance score.

Examples of climate parameters being used indirectly for design purposes are design flows for culverts or bridges as a function of rainfall, snowpack, streamflow, and temperature, or a combination. For such critical design information, the QP should engage a Climate Specialist and other experts, such as hydrologists or water resources experts, to define the climate parameters and values required. For example, to address specific issues of future hydrologic changes (e.g., changes in streamflow extremes, hydrologic regime shift from snow-dominated to rain-dominated, early snowmelt-driven freshet, and rain-on-snow events), input from a scientist or engineer with local knowledge and/or subject matter expertise should be sought.

By working with Climate Specialists and other experts, the QP is more likely to identify the appropriate specific climate parameters to use for the Risk Assessment, and is more likely to obtain accurate values that reflect projected climate conditions. Climate parameter projections normally provide a range of values. The QP must use professional judgment and methods (e.g., sensitivity analysis) to select the appropriate design value and document the rationale for the selection. Each Risk Assessment method or tool has its own specific format for documenting the climate parameters. The QP should follow the format unless there is a compelling reason to do otherwise.

Minimum Level of Effort

It is not always necessary to have specific numeric values for each of the general climate parameters identified in Section 3.2.3. It may be sufficient to determine whether the projected change for each parameter is large, moderate, or negligible, and whether the change is an increase or decrease from current values.

It is safe to assume that extreme events will reflect the magnitude and direction of changes with respect to the average values of a given climate parameter. For example, if climate models project a moderate increase to average precipitation, extreme values will, at the very least, reflect the changes to the averages of a given climate parameter. It may be useful to confer with a Climate Specialist to confirm these generalized assumptions.

3.3.5 IDENTIFY AND CHARACTERIZE INFRASTRUCTURE/CLIMATE INTERACTIONS

For each combination of listed infrastructure component and climate change parameter, the QP and assessment team must determine the type of interactions resulting from a climate event. If, for example, the current one-hour rainfall intensity with a 100-year return period were to increase by 50 percent[1], what might happen to the proposed catch basins, culverts, or ditch riprap? Could the catch basins become overwhelmed with increased runoff?

This portion of the Risk Assessment identifies the potential interactions between each infrastructure component and climate change parameter. Professional judgment and operational experience are required for making these decisions, as there is not an interaction for every combination of infrastructure component and climate change parameter.

Each assessment method specifies the format and process for documenting the interactions between each infrastructure component and specific climate parameters. This is to ensure consistency across various tasks of the assessment. Appendix B.6: A Summary of PIEVC Risk Assessments Conducted by the BC Ministry of Transportation and Infrastructure provides an example of a climate-infrastructure interaction table used in a Risk Assessment conducted under the PIEVC Engineering Protocol.

Minimum Level of Effort

There is little opportunity to reduce effort for this task, except perhaps in the level of documentation detail.

3.3.6 DETERMINE CLIMATE RISK

Within the context of infrastructure design and climate change, Climate Risk is a measure of how vulnerable a design component is to negative impacts of climate change. From a design perspective, a negative impact is a failure of the design component—either physically or in terms of performance criteria. Risk is a function of two attributes:

1. The probability, or likelihood, of the failure (or damage) to occur.
2. The severity of the consequences should the failure (or damage) occur.

Each Risk Assessment method provides guidance on how to define the scoring system. Scores could range from 0 to 7 for both “zero-to-high likelihood” and for “no-to-high severity,” as defined by the design team and stakeholders. For example, a likelihood score of 7 could be defined to mean “highly likely to occur” or “100-percent chance of occurrence” or “approaching certainty.” A severity score of 7 could be defined as “catastrophic” or “loss of asset.” It is very important to define levels of likelihood and severity/consequence to ensure consistency within the assessment; for example, what a score of 2 means on a likelihood scale, as opposed to a score of 5 on a 7-point scale.

Risk should be determined using the same definition and calculations for all identified interactions, as this provides consistency for the entire assessment process. The result will provide a more confident understanding of how vulnerable each selected infrastructure component is to each identified parameter.

Levels of the Risk Assessment include:

- screening of the interaction;
- Vulnerability analysis or assessment; and
- engineering analysis.

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[1] In Canada’s Changing Climate Report, Bonsal BR et al. (2019) project increases in future urban flooding as a result of increases in extreme precipitation.

Minimum Level of Effort

Provided each level is defined so all parties involved in the Risk Assessment understand what each level means when qualitatively estimating the level of confidence, it may be sufficient to define a simpler scoring system where the range of scores is less; for example, using 0 to 3 to represent "zero, low, medium, and high" likelihood, and "no, low, moderate, and high" severity or consequence.

3.3.6.1 Conduct Screening-Level Risk Assessment

Conducting a Screening-Level Risk Assessment allows the QP to determine the level of effort required on a Climate Change Risk Assessment, and to understand whether the project requires a comprehensive level of study. Each Risk Assessment task described in this section includes a statement about the required "minimum level of effort." By applying a minimum level of effort to each Risk Assessment task, these statements act to outline the process for the QP to follow when conducting a Screening-Level Risk Assessment and determining if the project requires more study.

The Screening-Level Risk Assessment is typically carried out as a desktop study. At a minimum, this assessment should:

1. select and characterize important infrastructure components to study; and
2. identify key climate variables that could impact those components.

When the Screening-Level Risk Assessment indicates that there may be moderate or high Climate Risks, it is prudent for the QP to arrange for a comprehensive Risk Assessment. This may require expanding the project team to provide additional information or expertise, conducting additional engineering analysis, defining climate change events in more detail, or any number of other actions.

The QP should consider a variety of factors when conducting a Screening-Level Risk Assessment:

- The Screening-Level Risk Assessment is intended to be a desktop study to understand broader climate change risk, with few resources and at low cost. For example, to evaluate potential risk, it might be possible to use high-level quantitative data on infrastructure (e.g., elevation, geographic location, existing flood protection) and readily available projected climate data or expert opinion (e.g., sea level rise, temperature increases, changes in streamflow).
- A simple matrix method could be sufficient to use when conducting a Screening-Level Risk Assessment. For example, assessing a small bridge replacement project where there is Vulnerability to future flow increases could involve conducting an engineering evaluation and estimating percentage flow increases.
- It is important to consider the scale of project, as developing a risk profile for an entire stretch of a highway or a new major highway interchange project could require more resources and time than what can be accomplished by a Screening-Level Risk Assessment. In such cases, conducting a full Climate Change Risk Assessment and engineering analysis may be necessary.

3.3.6.2 Conduct Risk Assessment

Once the potential interactions between the selected infrastructure components and defined climate change parameters have been determined, the completed Risk Assessment:

- assigns a likelihood (and/or frequency) score of each interaction occurring;
- assigns a severity score describing the consequences should the interaction occur; and
- calculates a risk score as the product of the likelihood and severity score.

In mathematical terms, risk = likelihood x severity.

It is important to determine the likelihood scores and severity scores separately. The QP cannot allow perceived severity to influence the assigned likelihood for a given interaction. The reverse is also true, where perceived likelihood cannot influence the assigned severity score. Documenting the reasons for separately selecting both the likelihood and severity for each interaction is useful when identifying Adaptation Measures.

The design team can reduce risk by:

- reducing the likelihood that the interaction will occur;
- reducing the severity of the interaction should it occur; or
- reducing both.

Minimum Level of Effort

The Screening-Level Risk Assessment is, at minimum, completed by the team identified in Section 3.2.4, to ensure a wide perspective and area of expertise are provided, which will increase confidence in results.

3.3.6.3 Evaluate Climate Change Risk Assessment

Quantifying the risk associated with each interaction between an infrastructure component and a climate parameter forms the basis for developing strategies to manage those risks.

For example, an infrastructure with low-risk scores does not require further consideration of climate change, while high-risk scores would require a Robust Design. Infrastructure components that are assigned "medium risk" scores may be candidates for Flexible Design or evaluated further to clarify risk and identify appropriate Adaptation Measures. In extenuating circumstances where "low risk" is the product of low likelihood and high severity, or of high likelihood and low severity, a comprehensive Risk Assessment will determine the tolerance and actual risks involved.

A sample risk matrix is shown in Figure 4 below.

SEVERITY								
7	0	7	14	21	28	35	42	49
6	0	6	12	18	24	30	36	42
5	0	5	10	15	20	25	30	35
4	0	4	8	12	16	20	24	28
3	0	3	6	9	12	15	18	21
2	0	2	4	6	8	10	12	14
1	0	1	2	3	4	5	6	7
0	0	0	0	0	0	0	0	0
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**

PROBABILITY

Special Case	Low Risk	Medium Risk	High Risk

Figure 4: Sample Risk Matrix

NOTE: Adapted from Engineers Canada (2011).

Note that application of the Risk Assessment results will depend on, to a large degree, the Owner's Climate Risk Tolerance. For example, if a coastal highway is at risk from flooding during a future extreme event, the Owner of the infrastructure must assess the importance of the highway to the community or economy, the remaining design life, and the adaptive capacity of the highway, to determine the necessary level of upgrades. Through this assessment, the Owner will also define their level of Climate Risk Tolerance, which will determine the level of Climate Change Resilience that must be incorporated into the design.

The EOR should review the Risk Assessment results and the recommended actions for each of the selected infrastructure components with the Highway Infrastructure Owner, and document the final decisions in the Highway Infrastructure Climate Change-Resilient Design Report.

Minimum Level of Effort

There is little opportunity to reduce effort for this task, except perhaps in the level of documentation detail.

3.3.6.4 Conduct Engineering Analysis

The Risk Assessment may require an additional engineering analysis to determine the level of risk associated with a particular interaction between an infrastructure component and climate parameter, if the initial assessment does not yield a defensible Vulnerability risk score. Typical triggers for an engineering analysis may include a medium-risk score that generates significant disagreements amongst team members on the degree of Vulnerability; interactions that tend to exhibit Vulnerability regardless of risk score; or insufficient data to make a definitive assessment.

The objective of an engineering analysis is to quantify the adaptive capacity, total load, and total capacity of the proposed design to climate change. The total load in an engineering analysis includes loads from climate and non-climate drivers, whereas total capacity includes design capacity adjusted for aging, normal wear, and other factors. When the total load exceeds total capacity, the infrastructure is vulnerable. If total load is less than total capacity, the infrastructure component has adaptive capacity and can be deemed resilient. These engineering analyses help establish the climate change safety factors for vulnerable components that provide the needed adaptive capacity, increase resilience, and reduce the risks to acceptable levels.

Another reason to conduct an engineering analysis is to facilitate the selection of Adaptation Measures. The contrast between design values generated by both current and projected future climate values are used to identify ways to reduce risk. For example, the hydraulic capacity required to convey peak flows generated from future climate values leads to increased conduit diameter, lowered roughness coefficient materials, attenuated peak flow from upstream storage, or a combination of two or more of these possibilities.

The three subsections below provide additional discussion regarding engineering analysis for each of the three primary engineering fields associated with the design of Highway Infrastructure: hydrotechnical, geotechnical, and structural.

Minimum Level of Effort

Engineering analysis at the component level is complex and time-consuming. It is normally reserved for components that are safety critical, and when professional judgment on the Climate Risk is divided or there are many unknowns that reduce confidence in the design process that will follow. The availability and quality of data is often an issue, which may be insufficient to improve the confidence of the design decisions that follow.

In such cases, conducting a sensitivity analysis may provide a better result. That is, rather than determining projected design climate values for load analysis, it may be sufficient to calculate capacity that would be required if the total load were increased by a specified amount. For example, if total load based on current design climate values were to increase by 10%, 25%, or even 50%, what impact would that have on the design's ability to provide the corresponding capacities?

3.3.6.4.1 Hydrotechnical Analysis

Hydrotechnical analysis supports the design of bridges, dykes, and large culverts for highway projects, as well as piers, jetties, and erosion protection for ports prone to stream bank and channel erosion, scour, stream diversions, and foreshore erosion. In many cases, design values are determined by conducting statistical analyses of historical records based on maximum flows. This approach may necessitate modelling and application of non-stationary methods, as historical records are no longer sufficient to provide projections of future climate conditions.

Modelling climate change impacts for every infrastructure design project may not be necessary. Sea level rise, for example, has already been modelled by several organizations and is available in the BC Ministry of Forests, Lands and Natural Resource Operation's *Flood Hazard Area Land Use Management Guidelines* (2018). Hydrologic models provide sufficient resolution of climate change predictions on larger streams, rivers, and watersheds; however, these models can also provide a useful basis for considering future conditions at a local or small stream scale. Engineering judgment is required to determine how to best estimate the impacts of climate change on the hydrotechnical design values required for each project.

3.3.6.4.2 Geotechnical Analysis

Geotechnical analysis supports the design of roads, bridge piers and abutments, culvert foundations and backfill, dykes, retaining walls, and rock-fall protection. Geotechnical design values—such as bearing capacity or slope stability—are dependent on physical properties of the soil (i.e., texture, moisture, and cohesion), groundwater table and flow, and bedrock presence and composition. None of these are climate parameters but they can be influenced by climate change.

Infrastructure built on permafrost, for example, are more susceptible to failure from a combination of warming and subsurface moisture. In the south, higher sustained temperatures may soften asphalt surfaces; increased freeze/thaw cycles can cause damage from frost heaves or thermal fatigue cracking, ultimately leading to increased cracking or rutting of the pavement surfaces due to reduced bearing capacity.

Changes in the average and extreme values of precipitation and temperature, including frequency and duration of events, can have significant impacts on geotechnical design. These considerable factors are part of any geotechnical analysis to support Climate Change Resilience in infrastructure design.

3.3.6.4.3 Structural Analysis

Structural analysis provides design values for a variety of materials and performance objectives, such as strength, durability, and, to a lesser extent, aesthetics. Durability of the structural components in passive or active mechanical systems, or at least their protective coatings, are subject to changes in temperature, solar radiation, wind speeds, precipitation, and moisture. Many of these climate parameters apply to structural design implicitly, rather than directly, as they are embedded into various structural codes. It is vital that the QP work with the structural team to identify appropriate climate parameters, to ensure changes to the accepted values are included in the analysis.

3.4 IDENTIFY AND INCORPORATE ADAPTATION MEASURES

For the purposes of these guidelines, the term "adaptation" refers to any action that reduces the Vulnerability of proposed infrastructure to the impacts of climate change. Infrastructure designed and constructed using an adaptation method is considered resilient for specified requirements of climate change.

These adaptive design strategies, outlined by the American Society of Civil Engineers (ASCE) in Climate-Resilient Infrastructure: Adaptive Design and Risk Management (ASCE 2018), minimizes regret—the mathematical difference between planned payoffs and best-performing payoffs under the same scenario. In certain cases (large-scale or high-risk projects) the EOR should also recommend a monitoring program to evaluate the infrastructure's resilience performance over time.

It is important to recognize that adaptation is not restricted only to increasing capacity or strength, but may include:

- enhanced operation and maintenance practices;
- different construction materials or methods;
- different siting;
- phasing opportunities triggered by threshold events;
- further study or more detailed analysis; and/or
- monitoring, or any number of items that could enhance Climate Change Resilience.

Adaptation reflects the following principles:

- Adaptive actions should be responsive and do not require complete understanding of climate change impacts, as there will always be some Uncertainty. Plans and actions should reflect current understanding of climate impacts.
- Adaptation often requires coordination across multiple sectors, geographical scales, and levels of government to build on the existing efforts and knowledge of a wide range of stakeholders. Because impacts, Vulnerability, and needs vary by region and locale, adaptation will be most effective when driven by local or regional risks and needs.
- Ecosystems provide valuable services that can help build Climate Change Resilience and reduce the Vulnerability to climate change impacts. Integrating the protection of biodiversity and ecosystem services into adaptation strategies will increase Climate Change Resilience.
- Adaptation should use strategies that complement or directly support other related climate or environmental initiatives, such as efforts to improve disaster preparedness or reduce greenhouse gas emissions.

The principles above are excerpted from the Progress Report of the Interagency Climate Change Adaptation Task Force: Recommended Actions in Support of a National Climate Change Adaptation Strategy (White House Council on Environmental Quality 2010).

3.4.1 EXERCISE PROFESSIONAL JUDGMENT

Given the level of public awareness of climate change issues, and by virtue of these guidelines, Engineering/Geoscience Professionals providing services for BCMoTI projects to which these guidelines apply cannot claim that they were unaware that climate change could potentially affect their professional work.

These guidelines do not require Engineering Professionals, specifically those acting as an EOR, to be subject matter experts on weather and climate issues. Rather, the expectation is that Engineering Professionals will, as part of their normal practice, determine where climate information is embedded in codes, standards, and assumptions and evaluate how the information is applied in their professional work.

Note that the key concept is that Engineering Professionals should consider the implications of climate change for their professional work and create a clear record of the outcomes of those considerations.

When acting as the EOR, Engineering Professionals should include the appropriate documentation of the rationale for decisions made using their professional judgment, to demonstrate that they have fulfilled their obligation for due diligence when considering climate. This will help defend against the potential for professional liability that the EOR assumes when approving a design. (See also Section 2.2.2 Engineer of Record.)

3.4.2 IDENTIFY ADAPTATION OPTIONS

This subsection introduces a range of Adaptation Measures that could be implemented to ensure the proposed infrastructure is able to withstand the impacts of climate change. Table 1: Suggested Standard of Practice of a Qualified Professional Conducting a Climate Change Risk Assessment, indicates the following five categories of Adaptation Measures that can be employed during the infrastructure design process:

- Status-Quo Design
- Flexible Design
- Robust Design
- Observational Method
- Low-or-No-Regret Strategies

3.4.2.1 Status-Quo Design

Status-Quo Design recognizes that implementing no explicit Adaptation Measures is a valid response, provided the QP documents the reason or reasons for this decision.

Situations where Status-Quo Design may be a valid design method include the following:

- The Risk Assessment shows that the infrastructure is at no risk or low risk due to climate change.
- The service life of the subject infrastructure is very short, and plans are made to reconsider Adaptation Measures when the infrastructure is replaced or refurbished.

3.4.2.2 Flexible Design

Flexible Design is based on the assumption that there will be opportunities to adapt in the future. This option reduces up-front capital costs by designing the infrastructure using climate values based on historical or projected climate values. It is important, therefore, to identify the consequences of the worst-case climate scenario unfolding after the infrastructure is constructed, and to have a plan of action to modify or upgrade the infrastructure accordingly. Within this context, the term “worst-case scenario” refers to the possibility that future design climate values are best represented by the maximum values in the range of climate projection results. If it is not feasible to develop a response plan to climate conditions that are worse than designed for, the Flexible Design option should not be used.

Adaptation Measures can be implemented as part of the initial design or when predefined trigger events occur. Trigger events should be defined in a way that ensures continued integrity of the subject infrastructure—that is, no failures—but still signals increasing likelihood that the climate is trending toward conditions more severe than those used for initial design. For example, a trigger may be an event flood level, flow rate, or rainfall intensity that reaches or exceeds a threshold.

Flexible Design is the ability to implement one or more of the following measures in the future:

- Increase the infrastructure’s capacity or capacities
- Reduce loads
- Reduce the consequences of failure

Note that Flexible Design is more appropriate for gradual changes over time, such as sea level rise or melting permafrost. Successful Flexible Design also requires monitoring of climate, loads, and infrastructure performance, and should only be implemented if the Owner has the funds, authority, and willingness to maintain the monitoring program and implement the predetermined upgrades as required.

3.4.2.3 Robust Design

Robust Design has the objective of ensuring that the proposed infrastructure will perform as expected over a range of possible future climate conditions, including the “worst-case” design scenario (as defined above). This option usually results in higher initial construction costs for the infrastructure and ultimately lower risk of Vulnerability to climate change.

Other considerations for choosing the Robust Design approach may be as follows:

- The overall cost of implementing Flexible Design far exceeds the additional cost of implementing Robust Design.
- Flexible Design is not an option because there are no feasible opportunities to phase in Adaptation Measures.
- There are social or political issues that are better addressed through Robust Design.

Robust Design may include, but is not limited to, the following:

- Use of generous safety factors applied to loads generated using “average” projected climate values, and ensuring that capacities are designed accordingly
- Capacities designed to service loads generated using “worst-case” projected design climate values
- Redundant features added to the design to protect against failure

3.4.2.4 Observational Method

The Observational Method, which is a technique under the Flexible Design approach, reduces initial construction costs by establishing a course of action and design modification for every foreseeable unfavorable deviation from the most-probable weather and climate condition (ASCE 2018; Terzaghi and Peck 1948).

Particular to geotechnical engineering, the Observational Method is most appropriate to locations that may be subjected to gradual changes in climate conditions (e.g., sea-level rise or permafrost melting as temperatures increase) and less applicable where sudden extreme climate events can inflict safety concerns or damages on the Highway Infrastructure (ASCE 2018). Examples of the Observational Method in practice can be found in the ASCE manual titled Climate-Resilient Infrastructure: Adaptive Design and Risk Management (ASCE 2018).

Steps of the Observational Method for Climate Change-Resilient Design for Highway Infrastructure, modified from ASCE (2018) and Terzaghi and Peck (1948), are listed below:

- Base the project design on the most-probable weather or climate conditions, as opposed to the most-unfavorable conditions. This method uses deviations from the most-probable conditions to determine the most-credible unfavorable conditions.
- Establish a course of action and design modification for every foreseeable unfavorable deviation from the most-probable weather and climate condition.
- Conduct a continuous monitoring program to determine the performance of the Highway Infrastructure to evaluate its performance and assess effectiveness to observed changes.
- Implement a plan of action to modify design and construction in response to observed climate changes.

3.4.2.5 Low-or-No-Regret Strategies

ASCE (2018) defines “regret” as the mathematical difference between planned payoffs and best-performing payoffs under the same scenario. In practice, the low-regret strategies are formulated policies that work under both current and uncertain future climates.

Low-or-No-Regret Strategies can offer co-benefits under a range of current climate change scenarios, and lay the foundation for addressing projected changes. These strategies include early warning systems, sustainable land-use planning, ecosystem management and restoration, and risk communication between decisionmakers and local residents to minimize the scope for maladaptation. The Intergovernmental Panel on Climate Change (IPCC) document titled Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (IPCC 2012) provides a detailed framework of the low-or-no-regret strategies.

Note that the EOR is responsible for selecting either one of the design approaches identified above or an alternative approach, based in part on the results of the Risk Assessment. Regardless of which design approach selected, it is essential to include a maintenance program to ensure design integrity over the service life of the infrastructure. All designs assume a level of operations and maintenance to ensure resilience over time.

The EOR must document all assumptions in the Highway Infrastructure Climate Change-Resilient Design Report.

Minimum Level of Effort

If the Screening-Level Risk Assessment indicates that the infrastructure has no Vulnerabilities to climate change, then, in consultation with the Owner, the infrastructure design could proceed without incorporating any Adaptation Measures. If the Screening-Level Risk Assessment indicates only low Climate Risk, it may be appropriate to implement simple adaptive or maintenance measures.

Irrespective of the type of Adaptive Measures being implemented into the design, or the lack of measures, the corresponding assumptions and reasons for the decision must be clearly documented. Information about the project-specific adaptation cost estimate for the chosen Adaptation Measures must also be documented in the BCMoTI Design Criteria Sheet.

3.4.3 COMMUNICATE EFFECTIVELY

Usually, the EOR does not make all decisions with respect to implementing climate change Adaptation Measures for a design. The language used to communicate concepts and principles can be interpreted differently by different parties, so it is important to effectively communicate highly technical information to decisionmakers who may have little or no technical knowledge or experience. The BCMoTI has published a document titled Developing Effective Dialogue between Practitioners of Climate Change Vulnerability-Risk Assessments: A Primer for Understanding Concepts, Principles and Language Use Across Disciplines (Revision 6) that addresses this issue within the context of climate and climate projections (BCMoTI 2014).

Given the critical importance of these issues, it is the QP’s professional responsibility to facilitate clear and effective communication within the team, and define technical terms where appropriate.

At times, the EOR may have to communicate climate issues, risks, and proposed Adaptation Measures to non-receptive decisionmakers. In such cases, the EOR must ensure the decisionmaker clearly understands the consequences of ignoring or rejecting the recommended Adaptation Measures. Furthermore, if the EOR believes that public health and safety are at significant risk if the Adaptation Measures are excluded from the design, it is the EOR’s professional responsibility to communicate such information more broadly—first by contacting Engineers and Geoscientists BC to seek council and advice, and, if appropriate, by notifying regulators and/or other external agencies.

Although it is the Highway Infrastructure Owner’s decision to accept or decline the recommended Adaptation Measures, the EOR should be aware that simply recommending actions to decisionmakers is not sufficient to fulfill their own professional responsibility. Where appropriate, the EOR should communicate to the Owner any ethical, legal, or safety concerns from not implementing the Adaptation Measures that the EOR has identified .

Minimum Level of Effort

There is little opportunity to reduce effort for this task, except perhaps in the level of documentation detail.

3.4.4 FINALIZE ADAPTATION PLAN AND RESILIENT DESIGN MEASURES

Once Resilient Design measures have been identified and organized into options, the Adaptive Measures must be presented to the Owner and other appropriate decisionmakers with the following information:

- A list of the interactions between the infrastructure and climate change that are addressed by the Adaptation Measures. This should include descriptions of the interactions, the assigned risk scores, and a summary of the likelihood and consequence severity scores that generate the risk scores—information that is readily available from the Risk Assessment.
- A description of how the Adaptation Measure would be implemented, especially if it is a Flexible Design measure as opposed to a Robust Design measure.
- An estimate of the financial impacts of implementing the proposed Adaptation Measure (adaptation cost estimate).
- A discussion of any related issues that could impact the implementation of the Adaptation Measure (e.g., ongoing monitoring, land acquisition, product sourcing, schedule impacts).

Minimum Level of Effort

The level of effort for this task will correspond to the number and types of Adaptation Measures incorporated into the design.

3.5 DOCUMENT PROCESS AND DECISIONS

It is critical to document key information associated with incorporating Climate Change Resilience into the Highway Infrastructure design process. In addition to fulfilling the quality assurance and quality control requirements of the Association's Bylaws and quality management guidelines, such documentation will prove valuable for the following:

- Developing and executing operation and maintenance plans
- Maintaining the monitoring programs
- Addressing upgrading or refurbishment issues
- Demonstrating due diligence, should there be a failure caused by a climate event

The QP is responsible for overseeing the design, preparation, and implementation of the Risk Assessment(s), as outlined in these guidelines, and informing the Client through the fulfillment of all appropriate documents. It is important to note that the BCMoTI Climate Change Risk Assessments Assurance Statement provides assurance that the professional has followed the suggested standard of practice as defined in these guidelines. It does not guarantee that a specific design will perform without issue under future climate conditions.

The BCMoTI Design Criteria Sheet for Climate Change Resilience and the Climate Change Risk Assessment Assurance Statement are available in Appendix A.

For BCMoTI projects, the QP completes the Assurance Statement and submits it along with the BCMoTI Design Criteria Sheet and the report outlining the results of the Risk Assessment, as outlined in Section 2.2.3 Qualified Professional.

At minimum, the report should include key information from each of the tasks outlined in Sections 3.3 to 3.5 of these guidelines. This key information may include, but is not limited to, the following:

- Risk Assessment and design team members, including their qualifications and roles
- Design criteria and associated references
- Data sources and corresponding uncertainties, data gaps, and assumptions (each Risk Assessment method may specify the format for this information)
- Reasons for selecting the infrastructure components and climate change parameters used for the Risk Assessment
- Scoring methods for likelihood and consequence severity
- Engineering analysis objectives, results, and conclusions
- Design values and adjustments for future climate where appropriate
- Adaptation Measures other than adjusted design values (e.g., siting changes, monitoring programs, actions to be taken when thresholds are triggered)
- Key decisions with respect to the Adaptation Measures selected for implementation and the corresponding justification for their selection
- The ensemble of climate models used in the Risk Assessment
- Climate projections used in the Risk Assessment
- Emissions scenario(s) considered in the Risk Assessment
- Name and version of Risk Assessment tools used in the assessment
- Time horizon used for the Risk Assessment

The EOR should also complete the BCMoTI Design Criteria Sheet for Climate Change Resilience and ensure it is submitted as required by the BCMoTI (Appendix A).

Minimum Level of Effort

Should the Screening-Level Risk Assessment adequately indicate low or no infrastructure Vulnerabilities to climate change, the document may be limited to summary statements of each of the items listed above. However, it is essential to state the reasons for making the assumptions and decisions.

4.0 QUALITY MANAGEMENT IN PROFESSIONAL PRACTICE

4.1 QUALITY MANAGEMENT REQUIREMENTS

Engineering/Geoscience Professionals must adhere to the applicable quality management requirements during all phases of the work, in accordance with the Association's Bylaws. It is also important to be aware of whether additional quality management requirements exist from authorities having jurisdiction or through service contracts.

To meet the intent of the quality management requirements, Engineering/Geoscience Professionals must establish and maintain documented quality management processes for the following activities:

- The application of relevant professional practice guidelines
- Authentication of professional documents by the application of the professional seal
- Direct supervision of delegated professional engineering/geoscience activities
- Retention of complete project documentation
- Regular, documented checks using a written quality control process
- Documented field reviews of engineering/geoscience designs/recommendations during implementation or construction
- Where applicable, documented independent review of structural designs prior to construction

4.1.1 PROFESSIONAL PRACTICE GUIDELINES

In accordance with the *Act*, s.4(1) and Bylaw 11(e)(4)(h), Engineering/Geoscience Professionals are required to comply with the intent of any applicable professional practice guidelines related to the engineering or geoscience work they undertake. One of the three objectives of the Association, as stated in the *Act* is "to establish, maintain, and enforce standards for the qualifications and practice of its members and licensees". Practice guidelines are one means by which the Association fulfills this obligation.

These professional practice guidelines establish the standard of practice for Climate Change-Resilient Design of Highway Infrastructure. Engineering/Geoscience Professionals who carry out these activities, and particularly the Engineer of Record (EOR), are required to meet the intent of these guidelines.

4.1.2 USE OF SEAL

In accordance with the *Act*, s.20(9), Engineering/Geoscience Professionals are required to seal all professional engineering or professional geoscience documents they prepare or deliver in their professional capacity to others who will rely on the information contained in the documents. This applies to documents that Engineering/Geoscience Professionals have personally prepared and those that others have prepared under their direct supervision.

Failure to seal these engineering or geoscience documents is a breach of the *Act*. For more information, refer to *Quality Management Guidelines – Use of Seal* (Engineers and Geoscientists BC 2017).

4.1.3 DIRECT SUPERVISION

In accordance with the *Act*, s.1(1) and 20(9), Engineering/Geoscience Professionals are required to directly supervise any engineering or geoscience work they delegate. When working under the direct supervision of an Engineering/Geoscience Professional, unlicensed persons or non-members may assist in performing engineering and geoscience work, but they may not assume responsibility for it. Engineering/Geoscience Professionals who are limited licensees may only directly supervise work within the scope of their license.

With regard to direct supervision, the Engineering/Geoscience Professional having overall responsibility should consider:

- the complexity of the project and the nature of the risks;
- which aspects of the work should be delegated;
- the training and experience of individuals to whom work is delegated; and
- the amount of instruction, supervision, and review required.

Careful consideration must be given to delegating field reviews. Due to the complex nature of field reviews, Engineering/Geoscience Professionals with overall responsibility should exercise judgment when relying on delegated field observations, and should conduct a sufficient level of review to have confidence in the quality and accuracy of the field observations. (See Section 4.1.6 Documented Field Reviews During Implementation or Construction.)

For more information, refer to *Quality Management Guidelines – Direct Supervision* (Engineers and Geoscientists BC 2018b).

4.1.4 RETENTION OF PROJECT DOCUMENTATION

In accordance with Bylaw 14(b)(1), Engineering/Geoscience Professionals are required to establish and maintain documented quality management processes that include retaining complete project documentation for a minimum of ten (10) years after the completion of a project or ten (10) years after engineering or geoscience documentation is no longer in use.

These obligations apply to Engineering/Geoscience Professionals in all sectors. Project documentation in this context includes documentation related to any ongoing engineering or geoscience work, which may not have a discrete start and end, and may occur in any sector.

Many Engineering/Geoscience Professionals are employed by organizations, which ultimately own the project documentation. Engineering/Geoscience Professionals are considered compliant with this quality management requirement when a complete set of project documentation is retained by the organizations that employ them using means and methods that are consistent with the Association's Bylaws and guidelines.

For more information, refer to *Quality Management Guidelines – Retention of Project Documentation* (Engineers and Geoscientists BC 2018c).

4.1.5 DOCUMENTED CHECKS OF ENGINEERING AND GEOSCIENCE WORK

In accordance with Bylaw 14(b)(2), Engineering/Geoscience Professionals are required to perform a documented quality checking process of engineering and geoscience work, appropriate to the risk associated with that work.

Regardless of sector, Engineering/Geoscience Professionals must meet this quality management requirement. In this context, 'checking' means all professional deliverables must undergo a documented quality checking process before being finalized and delivered. This process would normally involve an internal check by another Engineering/Geoscience Professional within the same organization. Where an appropriate internal checker is not available, an external checker (i.e., one outside the organization) must be engaged. Where an internal or external check has been carried out, this must be documented.

Engineering/Geoscience Professionals are responsible for ensuring that the checks being performed are appropriate to the level of risk. Considerations for the level of checking should include the type of document and the complexity of the subject matter and underlying conditions; quality and reliability of background information, field data, and elements at risk; and the Engineering/Geoscience Professional's training and experience.

An independent peer review is an additional level of review beyond the minimum requirements of Bylaw 14(b)(2) that may be undertaken for a variety of reasons by an independent peer reviewer not previously involved in the project. For example, the independent peer review could be requested by the Owner or required as a part of a legal/technical investigation resulting from a complaint or a lawsuit. The peer reviewer will review the Risk Assessment and the report to determine the accuracy of the findings and the validity of the recommendations.

For more information, refer to *Quality Management Guidelines – Documented Checks of Engineering and Geoscience Work* (Engineers and Geoscientists BC 2018d).

4.1.6 DOCUMENTED FIELD REVIEWS DURING IMPLEMENTATION OR CONSTRUCTION

In accordance with Bylaw 14(b)(3), field reviews are reviews conducted at the site of the construction or implementation of the engineering or geoscience work. They are carried out by an Engineering/Geoscience Professional or a subordinate acting under the Engineering/Geoscience Professional's direct supervision (see Section 4.1.3 Direct Supervision).

Field reviews enable the Engineering/Geoscience Professional to ascertain whether the construction or implementation of the work substantially complies in all material respects with the engineering or geoscience concepts or intent reflected in the engineering or geoscience documents prepared for the work.

For more information, refer to *Quality Management Guidelines – Documented Field Reviews during Implementation or Construction* (Engineers and Geoscientists BC 2018e).

4.1.7 DOCUMENTED INDEPENDENT REVIEW OF STRUCTURAL DESIGNS

Bylaw 14(b)(4) refers to an independent review in the context of structural engineering. An independent review is a documented evaluation of the structural design concept, details, and documentation based on a qualitative examination of the substantially complete structural design documents, which occurs before those documents are issued for construction. It is carried out by an experienced Engineering Professional qualified to practice structural engineering, who has not been involved in preparing the design.

For more information, refer to *Quality Management Guidelines – Documented Independent Review of Structural Designs* (Engineers and Geoscientists BC 2018f).

5.0 PROFESSIONAL REGISTRATION & EDUCATION, TRAINING, AND EXPERIENCE

5.1 PROFESSIONAL REGISTRATION

An Engineering Professional who is engaged in work related to public infrastructure is typically registered with Engineers and Geoscientists BC in the discipline of geotechnical, structural, civil or hydro-technical engineering. However, not all Engineering Professionals registered in these disciplines are necessarily appropriately knowledgeable in Risk Assessments.

It is therefore the responsibility of Engineering/Geoscience Professionals to determine whether they are qualified by training and/or experience to undertake and accept responsibility for conducting Climate Change Risk Assessments as a Qualified Professional (QP), or for carrying out Climate Change-Resilient Design of Highway Infrastructure as an Engineer of Record (EOR) (Code of Ethics Principle 2).

5.2 EDUCATION, TRAINING, AND EXPERIENCE

Developing Climate Change-Resilient Designs for Highway Infrastructure, as described in these guidelines, requires minimum levels of education, training, and experience in many overlapping areas of engineering and geoscience. The Engineering/Geoscience Professional taking responsibility must adhere to the Association's Code of Ethics (to undertake and accept responsibility for professional assignments only when qualified by training or experience) and, therefore, must evaluate his or her qualifications and must possess the appropriate education, training, and experience to provide the services.

The level of education, training, and experience required of the Engineering/Geoscience Professional should be adequate for the complexity of the project. Typical qualifications for the lead Engineering/Geoscience Professional or a team of professionals may include education and experience in the following areas:

- Climate science and climate data
- Risk Assessment methodologies
- Adaptation-specific tools

The academic training for the above skill sets can be acquired by taking formal university or college courses or through continuing professional development. There may be some overlap in courses and specific courses may not correlate to specific skill sets. An Engineering/Geoscience Professional should also remain current with evolving topics, through continuing professional development. Continuing professional development can include taking formal courses; attending conferences, workshops, seminars, and technical talks; reading technical publications; doing web research; and participating in field trips.

At minimum, an Engineering/Geoscience Professional acting in the capacity of a QP should have the following skills and experience:

- Has worked in a multi-stakeholder team in conjunction with an Owner to conduct Risk Assessments
- Can work with a Climate Specialist to acquire the appropriate regional climate data projections
- Can use regional climate data projections in a Risk Assessment
- Can recommend adaptation methods for design of the Highway Infrastructure based on the Risk Assessment
- Can clearly document the results of the Risk Assessment to communicate the risks due to climate change to the Owner

6.0 REFERENCES AND RELATED DOCUMENTS

Documents cited in the main guidelines appear in Section 6.1: References; documents cited in appendices appear in a reference list at the end of each appendix.

Related documents that may be of interest to users of these guidelines but are not formally cited elsewhere in this document appear in Section 6.2: Related Documents.

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7.0 APPENDICES

LIST OF APPENDICES	PAGE

APPENDIX A: BCMOTI DESIGN CRITERIA SHEET AND ASSURANCE STATEMENT

LIST OF APPENDICES PAGE

A.1: BCMoTI TECHNICAL CIRCULAR T-04/19, INCLUDING DESIGN CRITERIA SHEET FOR CLIMATE CHANGE RESILIENCE

Technical Circular T-04/19
Date: March 27, 2019

To: All TRAN Staff

Subject: Resilient Infrastructure Engineering Design - Adaptation to the Impacts of Climate Change and Weather Extremes

Requirements:

- Provide engineering design adaptation to climate change and weather extremes using climate projections and risk analysis
- Submit a Design Criteria Sheet for Climate Change Resilience (Appendix 1) to the Chief Engineer's Office

Purpose:
This technical circular supersedes Technical Circular T-06/15 - Climate Change and Extreme Weather Event Preparedness and Resilience in Engineering Infrastructure Design.

Given the potential for climate change to impact transportation infrastructure in BC, it is prudent to develop directives and guidance for incorporating climate adaptation into engineering designs provided to the BC Ministry of Transportation and Infrastructure.

Thus, the Ministry requires engineering design work to evaluate risk and include adaptation measures to the impacts of future climate change, weather extremes and climate-related events, as well as changes in average climate conditions. This policy applies to all new projects, as well as rehabilitation and maintenance projects.

Supporting resources for this policy, such as practice guidance, adaptation project-examples and risk assessment methods, can be obtained from sources such as professional associations. Climate information can be obtained from climate resource providers. Some of these resources are found on the BCMoTI Climate Change and Adaptation website.

This policy aligns with the BC Climate Action Plan - in developing strategies to help BC adapt to the effects of climate changes. And therefore, the Ministry will continue to provide a provincial transportation system that is resilient, reliable and efficient regardless of unfolding impacts of climate change,

Background:
Climate change impacts are being felt in communities across the province with more frequent and intense weather extremes and climate-related events causing damage to infrastructure, property, and ecosystems. Therefore, climate change adds additional challenges to environmental risks of flood, wildfire, landslide, geologic subsidence, rock falls, avalanche, snow, ice, temperature extremes and variability, extreme precipitation, and storms of various intensities.

Furthermore, the design life of transportation infrastructure is inherently long, thus service requirements for roads, bridges, tunnels, railways, ports and runways may be required for decades, while rights-of-way and specific facilities may continue to be used for transportation purposes for much longer. Thus, climate change presents added risks to the long-term reliability of interconnected systems that are already exposed to a range of stressors such as aging and deteriorating infrastructure, environmental risks, land-use changes, and population growth.

Consequently, infrastructure designers and operators must consider the magnitude of potential stress that any project will be expected to withstand over its design life. While transportation infrastructure is currently designed to handle a broad range of impacts based on historic climate, preparing for future climate change and weather extremes and other climate related events as well as changes in average climate conditions is also to be considered.

Thus, preparing for implications regarding the design, construction, operation, and maintenance of transportation systems to future conditions is critical to protecting its integrity and current and future investment of taxpayer dollars and will result in wise use of resources.

Timeline: Effective immediately for all new engineering design assignments

Expectations:

1. Reasonable consideration of the impacts of future climate change and weather extremes appropriate to the scale of the project (including new, rehabilitation and maintenance projects)
2. Using risk assessment methods and climate information for design work from sources such as those providers listed in Appendix 4 (and on the BCMoTI Climate Change and Adaptation website)
3. At the concept stages, the project designer will identify the design components at risk from the impacts of future climate change and weather extremes over the expected project design life
4. At the concept stages, the project designer will summarize changes in temperature, precipitation and other climatic variables over the expected project design life
5. The project designer will identify the risks to project design components from these projected climate changes and summarize the risks in the BCMoTI Climate Change Design Criteria Sheet for Climate Resilience (Appendix 1)
6. The project designer will develop adaptation design strategies to address climate change risks for the project
7. Based on evaluation of future climate change effects and impacts, the project designer will develop a project-appropriate set of design criteria for event preparedness and resiliency
8. Engineering design parameter evaluation and modification for adaptation to climate change will be summarized and listed on *BCMoTI Climate Change Design Criteria Sheet for Climate Resilience* (Appendix 1)
9. The design team will implement the developed design criteria into the project

Documentation:

Design Criteria Sheet for Climate Change Resilience (included below):

This document summarizes the impacts of future climate change and weather extremes and the implications to engineering project infrastructure components. Thus, this sheet will include a list of infrastructure components at risk of being impacted by future climate change events and detail adaptation measures and costs included in the infrastructure design. Please list the climate risks encountered for project components. Adaptation costs are the estimated costs of climate adaptation for the components of the project (such as increasing the size of culvert pipes, etc.). One criteria sheet is required per discipline involved in design work. All Design Criteria Sheets are to be submitted to the Chief Engineer's Office at: BCMoTI-ChiefEngineersOffice@gov.bc.ca.

(BCMoTI Design Criteria Sheet for Climate Change Resilience - Explanatory Notes/Discussion Example - included below)

This example provides guidance on the types of information to include in the Explanatory Notes/Discussion section of the BCMoTI Design Criteria Sheet for Climate Change Resilience.

Appendix 1: BCMoTI Design Criteria Sheet for Climate Change Resilience
Appendix 2: BCMoTI Design Criteria Sheet for Climate Change Resilience - Explanatory Notes/Discussion Example
Appendix 3: Scope of guidance and resources
Appendix 4: Climate adaptation and vulnerability analysis sources
Appendix 5: What definitions are used in this directive?

Contact:

Chief Engineer
BCMoTI-ChiefEngineersOffice@gov.bc.ca

[signed]

Dirk Nyland, P.Eng. IRP
Chief Engineer

Design Criteria Sheet for Climate Change Resilience

Highway Infrastructure Engineering Design and Climate Change Adaptation
BC Ministry of Transportation and Infrastructure
(Separate Criteria Sheet per Discipline)
(Submit all sheets to the Chief Engineers Office at:
BCMoTI-ChiefEngineersOffice@gov.bc.ca)

Project:	*(i.e. Project Name and Number)*
Type of work:	*(i.e. Capital/Rehab/reconstruction, Bridge Structures, Culverts, Interchange/Intersection/Access Improvement, Corridor Improvement, etc.)*
Location:	*(i.e. Road names (Major/Minor), Closet City, Municipality, Cardinal Directions, Electoral District, GPS, LKI Segment and KM reference, etc.)*
Discipline:	

Design Component	Design Life or Return Period	Design Criteria + (Units)	Design Value Without Climate Change	Change in Design Value from Future Climate	Design Value Including Climate Change	Adaptation Cost Estimate ($)	Comments / Notes / Deviations / Variances
Example Only: Culvert <3m	75 yr DL 100 yr RP	Rainfall Intensity (mm/h)	51.9	+40%	72.7	$X	- See work including climate projections
Example Only: Culvert <3m	100 yr RP	Flow Rate (m^3/s)	20	+10%	22	$X	- See work including climate projections
Example Only: Bridge	200 yr RP	Flow Rate (m^3/s)	82.8	+20%	99.3	$X	- See work including climate projections

Explanatory Notes / Discussion:

(Provide brief scope statement, purpose of project and what is being achieved. Enter comments for clarification where appropriate and provide justification and evidence of engineering judgment used for items where deviations are noted in the design parameters listed above or any other deviations which are not noted in the table above.)

Recommended by: Engineer of Record: ______________________________
(Print Name / Provide Seal & Signature)

Date: ______________________________

Engineering Firm: ______________________________

Accepted by BCMoTI Consultant Liaison: ______________________________
(For External Design)

Deviations and Variances Approved by the Chief Engineer: ______________________________
Program Contact: Chief Engineer, BCMoTI

Design Criteria Sheet for Climate Change Resilience

Highway Infrastructure Engineering Design and Climate Change Adaptation
BC Ministry of Transportation and Infrastructure
(Separate Criteria Sheet per Discipline)
(Submit all sheets to the Chief Engineers Office at:
BCMoTI-ChiefEngineersOffice@gov.bc.ca)

Project:	*(i.e. Project Name and Number)*
Type of work:	*(i.e. Capital/Rehab/reconstruction, Bridge Structures, Culverts, Interchange/Intersection/Access Improvement, Corridor Improvement, etc.)*
Location:	*(i.e. Road names (Major/Minor), Closet City, Municipality, Cardinal Directions, Electoral District, GPS, LKI Segment and KM reference, etc.)*
Discipline:	

(Design Criteria Sheet - Explanatory Notes/Discussion example)

Design Criteria

The drainage design criteria for the project are based on the principals outlined in the BCMoTI Supplement to TAC Geometrics Design Guide -1000 Hydraulics Chapter. This drainage assessment is limited to evaluating a single culvert. No pavement drainage, roadside ditches, or catch basin design is included in this scope of work. The design criteria noted below provide a summary of the key design items.

Hydrology

- Flow rates to be calculated using the Rational Method
- Rainfall Intensity Duration Frequency (IDF) Data to be based on Environment Canada's rain gauge, with 25 years of data from 1980-2007
- Time of concentration to be calculated using the Kirpich Formula and/or the Hathaway formula
- The runoff coefficient to be calculated using values from Table 1020.A in the Supplement to TAC

Culverts

- Culverts with spans less than 3000 mm are to be sized for the 100-year return period design flow rate
- Outlet-controlled culverts are to be sized to limit the head loss across the culvert to 300 mm
- Inlet-controlled culverts are to be sized to limit the headwater-to-diameter (HW/D) ratio to 1.0
- Minimum culvert diameter under a highway or main road is 600 mm

Design Life

As outlined in the BCMoTI Supplement to TAC Geometric Design Guide Hydraulics Chapter, the structural design life for culverts less than 3000 mm span shall be 75 years.

Climate Change Risk (Please include this section in all Design Criteria Sheet submissions)

In accordance with BCMoTI Climate Change Technical Circular {previously T-06/15), the potential impacts of future climate change need to be considered on all Ministry projects. For the drainage design components of this project, future climate change is anticipated to increase the amount of rainfall.

Climate Change Estimates

Climate Explorer - PCIC (Pacific Climate Impacts Consortium)

IDFCC (Western University Ontario)

Using the IDFCC tool to estimate increases to rainfall intensities for Environment Canada's rain gauge to the year 2067. Using the ensemble median of appropriate GCMs, and assuming a Representative Concentration Pathway (RCP) 8.5 climate change scenario, looked at the estimated increases to rainfall rates for a variety of return periods and storm durations. Looking at storm durations from 30 minutes to 2 hours for the 100-year return period, the estimated increase in rainfall intensity varies from 30% to 39%.

Flow Estimate

Estimated the 100-year peak flow rate for the culvert using the Rational Method. The peak flow is a function of the catchment area, runoff coefficient, and rainfall intensity. To account for climate change, applied an increase of 40%, resulting in a design rainfall intensity of 72.7 mm/h. Using these values, estimated a peak 100-year design flow rate of 0.11 m^3/s.

Results - Culvert Hydraulics

The existing culvert crossing under the highway is a corrugated steel pipe (CSP) and has a diameter of 800 mm. Estimated length of the culvert is approximately 30 m. At the design flow rate of 0.11 m3/s, the culvert has a head loss of less than 0.1 m under outlet control conditions; therefore, the culvert appears to have sufficient capacity.

Appendix 3

What is the scope and application of this guidance?

This directive pertains to transportation infrastructure engineering design work by BCMoTI staff and consultants and others working on projects for BCMoTI. Many parameters, such as type, location, traffic volume, and design life of transportation infrastructure will determine the scope and scale of climate change related analysis required.

In general, for transportation engineering design projects BCMoTI will require:

- Consideration of impacts of future climate change and weather extremes and climate-related events and changes in average climate conditions
- Assessment of Infrastructure and climate risk for the design life of components, indicating relevant information and sources
- Design that incorporates information, analyses and projections of the impact of future climate change and weather extremes
- Development of practical and affordable project design criteria which takes adaptation to climate change into account
- *BCMoTI Design Criteria Sheet for Climate Change Resilience* to summarize engineering design parameter evaluation and modification for adaptation to climate change

Where can I obtain guidance, climate resources and vulnerability analysis tools?
For more information and links to resources and tools related to the impacts of future climate change, weather extremes and adaptation to these, please see Appendix 4 (and the BCMoTI website on climate adaptation). These contain links to climate information providers such as the Pacific Climate Impacts Consortium, and risk analysis tools such as the Public Infrastructure Engineering Vulnerability Committee Protocol.

Appendix 4

Climate Adaptation and Vulnerability Analysis Sources

BCMoTI Climate Adaptation site

EGBC - Climate Change Practice Guidelines

Pacific Climate Impacts Consortium

Analysis Tools - Climate Explorer, Plan2Adapt etc

Pacific Institute for Climate Solutions

Climate Insights 101

Public Infrastructure Engineering Vulnerability Committee

IDF CC Tool (Western University Ontario)

Ouranos (Quebec)

Intergovernmental Panel on Climate Change (IPCC)

Federal Highway Administration - Climate Adaptation (USA)

AASHTO - Transportation and Climate Change Resource Center (USA)

Appendix 5

What definitions are used in this directive?

1. **Climate Change.** Climate change refers to any significant change in the measures of climate lasting for an extended period of time. Climate change includes major variations in temperature, precipitation, or wind patterns, among other environmental conditions, that occur over several decades or longer. Changes in climate may manifest as a rise in sea level, as well as increase the frequency and magnitude of extreme weather events now and in the future

2. **Extreme Weather Events.** Extreme weather events can include significant anomalies in temperature, precipitation and winds and can manifest as heavy precipitation and flooding, heatwaves, drought, wildfires and windstorms. Consequences of extreme weather events can include reliability concerns, damage, destruction, and/or economic loss. Climate change can also cause or influence extreme weather events

3. **Extreme Events.** For the purposes of this directive, the term "extreme events" refers to risks posed by climate change and extreme weather events. The definition does not apply to other uses of the term nor include consideration of risks to the transportation system from other natural hazards, accidents, or other human induced disruptions

4. **Preparedness.** Preparedness means actions taken to plan, organize, equip, train, and exercise to build, apply, and sustain the capabilities necessary to prevent, protect against, ameliorate the effects of, respond to, and recover from climate change related damages to life, health, property, livelihoods, ecosystems, and national security

5. **Resilience.** Resilience or resiliency is the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions

6. **Adaptation.** Adjustment in natural or human systems in anticipation of or response to a changing environment in a way that effectively uses beneficial opportunities or reduces negative effects

7. **PIEVC.** Public Infrastructure Engineering Vulnerability Committee

8. **PCIC.** Pacific Climate Impacts Consortium

A.2: CLIMATE CHANGE RISK ASSESSMENT ASSURANCE STATEMENT

CLIMATE CHANGE RISK ASSESSMENT ASSURANCE STATEMENT

Note: This statement is to be read and completed in conjunction with the Highway Infrastructure Climate Change-Resilient Design Report outlined in the *Professional Practice Guidelines – Developing Climate Change-Resilient Designs for Highway Infrastructure in British Columbia* ("the guidelines").

This Assurance Statement is to be provided when a Climate Change Risk Assessment has been completed for the purpose of retrofitting existing Highway Infrastructure or informing the design process for new infrastructure, as required by the British Columbia (BC) Ministry of Transportation and Infrastructure (BCMoTI). Defined terms are capitalized and underlined; see the **Defined Terms** section in the guidelines for definitions.

Note that this Assurance Statement provides assurance that the professional has followed the guidelines, and does not guarantee that a specific design will perform without any issues under future climate conditions.

To: BC Ministry of Transportation and Infrastructure
(or other BC Municipality) Date: ______________________________

____

____

Jurisdiction and address

With reference to (CHECK ONE):

- ☐ New design
- ☐ Retrofit
- ☐ Other (specify) ______________________________

For the Highway Infrastructure:

____

Legal description and GPS coordinates of the infrastructure

The undersigned hereby gives assurance that the attached Climate Change Risk Assessment reporting on the above-mentioned infrastructure substantially complies with the intent of the guidelines. The Highway Infrastructure Climate Change Resilient Design Report and the BCMoTI Design Criteria Sheet for Climate Change Resilience[1] must be read in conjunction with this statement.

[1] Technical Circular T-04/19, Climate Change and Extreme Weather Event Preparedness and Resilience in Engineering Infrastructure Design (BCMoTI 2019), identifies implications of climate change and extreme weather events for engineering project infrastructure components. The Design Criteria Sheet for Climate Change Resilience, which is part of the Technical Circular, lists infrastructure components impacted by climate change and extreme weather events and provides the Adaptation Measures included in the infrastructure design.

(Items in **BOLD** below indicate the minimum level of effort to be expended by the Qualified Professional in conducting the Climate Change Risk Assessment.)

In preparing the Highway Infrastructure Climate Change Resilient Design Report I have:

(CHECK TO THE LEFT OF APPLICABLE ITEMS)

___**1.** **Collected and reviewed appropriate background information, including service life of the infrastructure**

___**2.** **Reviewed the proposed or existing infrastructure development on the project**

___3. Conducted field work and reported on the results of the field work on and, if required, beyond the project

___**4.** **Assembled a qualified team in collaboration with the Owner**

___5. Considered any changed conditions on and, if required, beyond the project

6. For the Climate Change Risk Assessment, I have:
   - ___**6.1** **Reviewed and characterized, if appropriate, future climate and extreme weather event projections and analyses**
   - ___6.2 Worked with a climate data provider to obtain relevant future climate and extreme weather event projections
   - ___6.3 **Estimated the risk to the infrastructure using a BCMoTI/other Owner-acceptable risk screening analysis (such as the PIEVC Protocol)**
   - ___6.4 Included (if appropriate) the effects of climate change and land-use change
   - ___6.5 Identified existing and anticipated future components at risk on and, if required, beyond the project
   - ___6.6 Estimated the potential consequences to those components at risk

7. Where the BCMoTI has specified a specific level of Climate Risk Tolerance that is different from the standard design criteria, I have:
   - ___7.1 Compared the level of Climate Risk Tolerance adopted by the BCMoTI/other Owner with the findings of my investigation
   - ___7.2 Made a finding on the level of Climate Risk Tolerance on the infrastructure based on the comparison
   - ___7.3 Made recommendations to reduce the risk on the infrastructure

8. Where the BCMoTI has not specified a level of Climate Risk Tolerance, I have:
   - ___8.1 Described the method of risk assessment used
   - ___8.2 Described the assumptions used in arriving at climate projections
   - ___8.3 Where available, referred to an appropriate and identified provincial or national resource for level of risk
   - ___8.4 Compared the guidelines with the findings of my investigation
   - ___8.5 Made a finding on the level of Climate Risk Tolerance for the infrastructure based on the comparison
   - ___8.6 Made recommendations to reduce risks

___9. Reported on the requirements for future inspections of the infrastructure and recommended who should conduct those inspections

___10. Suggested an operations and maintenance schedule to ensure that climate resilience and operational liability are addressed

Based on my comparison between:

(CHECK ONE):

- ☐ The findings from the investigation and the adopted level of Climate Risk Tolerance (item 7 above); or
- ☐ The appropriate and identified provincial or national guideline for level of Climate Risk Tolerance (item 8 above)

I hereby give my assurance that the standard of practice established in the guidelines has been applied in conducting the Climate Change Risk Assessment, documenting the results in the Highway infrastructure Climate Change Resilient Design Report, and informing the design of the Highway Infrastructure.

I certify that I am a Qualified Professional as defined in the guidelines.

______________________________ ______________________________

Name (print) Date

____

Signature

____

Address

____

____

Telephone

____

Email (Affix PROFESSIONAL SEAL here)

If the Qualified Professional is a member of a firm, complete the following:

I am a member of the firm ____

(Name of firm)

and I sign this letter on behalf of the firm.

APPENDIX B: ADAPTATION EXAMPLES FROM PRACTISING PROFESSIONALS

Climate science as it relates to professional engineering is constantly evolving. The examples of case studies and Highway Infrastructure Climate Change-Resilient Design Reports in this appendix illustrate methods that can be used to incorporate climate change considerations into design.

Feedback received on these guidelines will inform future updates, and users who have successfully applied these guidelines to the design of Highway Infrastructure are encouraged to submit copies of their Highway Infrastructure Climate Change-Resilient Design Reports to the Association.

Submitted case studies and reports may be considered for inclusion in future updates to these guidelines or in the Association's online Climate Change Information Portal (egbc.ca/Practice-Resources/Climate/Climate-Change-Information-Portal).

To submit a report, contact Harshan Radhakrishnan, P.Eng., Engineers and Geoscientists BC Manager, Climate Change and Sustainability Initiatives (email:hrad@egbc.ca).

LIST OF APPENDICES PAGE

B.1 COMMOTION CREEK CULVERT (07037) REPLACEMENT – 2016 SOUTH PEACE FLOOD RECOVERY PROGRAM

Submitted by: Des Goold, P.Eng., Principal, Northwest Hydraulic Consultants

Design Criteria Sheet for Climate Change Resilience

Highway Infrastructure Engineering Design and Climate Change Adaptation
BC Ministry of Transportation and Infrastructure
(Separate Criteria Sheet per Discipline)
(Submit all sheets to the Chief Engineers Office at:
BCMoTI-ChiefEngineersOffice@gov.bc.ca)

Project:	Commotion Creek Culvert (07037) Replacement – 2016 South Peace Flood Recovery Program
Type of work:	Culvert Replacement with a bridge (Concept to Detailed Design)
Location:	Highway 97; BCMoTI Northern Region
Discipline:	Hydrotechnical

Design Component	Design Life or Return Period	Design Criteria + (Units)	Design Value Without Climate Change	Change in Design Value from Future Climate	Design Value Including Climate Change	Adaptation Cost Estimate ($)	Comments / Notes / Deviations / Variances
Replacement Bridge (37 m clear span)	200 yr	Flow Rate (m^3/s)	213	+20%	255	$71,570 (1% of construction cost)	- Design Flood elevation rises by 0.2m - 200-year average velocity increases by 0.2 m/s - Riprap Class 500-kg thickness increased from 1.2 m to 1.5 m

Explanatory Notes / Discussion

The BC Ministry of Transportation and Infrastructure (BCMoTI) is intending to replace Commotion Creek Culvert No. 07037 located approximately 20 km west of Chetwynd on Highway 97. The existing crossing consists of one, 26 m long 3,000 mm CSP (corrugated steel pipe), and two, 33 m long 2,700 mm CSPs. Only the 3,000 mm CSP existed prior to and during the 2016 South Peace Flood; the other two CSPs were added after the flood as a short-term measure to reduce the possibility of future flood damage. The 3,000 mm culvert was drastically undersized and unable to handle the flood in June 2016, which led to a substantial amount of flow being diverted to the east of Commotion Creek where it did significant damage to highway, railway, and pipeline infrastructure. The BCMoTI' s intent is to replace the existing set of culverts with a new, 37 m long, clear span bridge. The existing approach channel upstream of the highway has aggraded and filled in over several decades and is itself undersized, and it will become unstable if exposed to unconstrained flows allowed by the new bridge; therefore, a 220 m length of the approach channel will be widened, re-graded, and armoured to help ensure its future stability. Northwest Hydraulic Consultants Ltd. (NHC) has been retained by the BCMoTI under General Services Contract 356CS0874/ 0896 to prepare a Hydrotechnical Assessment and Design Report for the new Commotion Creek Bridge and channel.

The effect of climate change on the flood hydrology for Commotion Creek has been assessed by analyzing future projections in rainfall intensity at nearby climate stations, as well as future projections in streamflow for some of the larger rivers in the region (streamflow projections are not available for streams in the size range of Commotion Creek). The hydrologic impacts of climate change will be partly attributed to changes in rainfall intensity, but the Commotion Creek watershed is too large for rainfall intensity to be the primary factor. There are numerous other climate indicators that will be affected as well, including changes to temperature normals, and the spatial and temporal variation in precipitation throughout the year, etc.

The projected impact on rainfall intensity has been evaluated by using IDF-CC, an online tool developed by Srivastav, Schaardong, and Simonovic (2014) that applies the downscaled global circulation model (GCM)'s output to modify present intensity-duration-frequency (/OF) curves published by (ECCC)1. The IDF-CC tool produces ensemble predictions from the full suite of climate projections from Assessment Report 5 (AR5) of the United Nations Intergovernmental Panel on the Climate Change (IPCC 2014). AR5 output is produced for three Representative Concentration Pathway (RCP) scenarios (RCP 8.5, RCP 4.5, and RCP 2.6). RCP 8.5, for example, refers to the projected change in radiative forcings (+8.5 Wlm^2) in the year 2100 relative to pre- industrial levels. While RCP 8.5 is the worst-case scenario of greenhouse gas concentration trajectories referred to in the IPCC report, it is the general consensus among local climate change scientists that RCP 8.5 is the likely pathway given the current state of anthropogenic (human) activity.

The online IDF-CC tool also allows the user to input historical rainfall data, which can be used to generate locally relevant updated IDF curves, and adjust for climate change based on the same method for the ECCC data. NHC used the IDF-CC tool to produce estimates of changes in rainfall intensities over different durations, time periods, and RCPs for the BCFF Stations at Lemoray, Hudson’s Hope, and Noel, and the ECCC Stations at Chetwynd and Dawson Creek. The results of the analysis show that for RCP 8.5, the increase in rainfall intensities by the end of the 2151st Century could be as much as 25%.

To assess the impacts of climate change on larger rivers, NHC carried out non-stationary flood frequency analysis on the Pine River (12,000 km^2) and Moberly River (1,520 km^2). The projections were developed by the Pacific Climate Impacts Consortium (PCIC). Unfortunately, there are no projections for streams of an intermediate size. The analysis results show that there is not a consistent regional signal in terms of the magnitude and direction of changes in peak flows on the larger rivers in the region. In NHC’s judgement, systems in the mountainous region of the South Peace have physiography similar to the Pine River (i.e., Murray River, Sukunka River).

For smaller watersheds in the mountainous region, and for all watersheds on the Alberta Plateau, larger floods tend to be rainfall-driven as opposed to snowmelt-driven. Therefore, the estimate median increases in rainfall intensity should be directly applied to design flows for those streams. There should be some reduction in the percent increase in flows as watershed size increases. At this time, NHC recommends applying a 25 percent increase in the 100- and 200-year flow for the smallest watersheds (under 25 km^2 in size), a 15 percent increase for larger watersheds (1,000 km^2 and larger), and a 20 percent increase for watersheds sizes in between those limits. Accordingly, the 200-year design flood for Commotion Creek should incorporate 20 percent increase to account for climate change. NHC recommends that 200-year peak discharge of 255 m^3/s be adopted as the design discharge for the replacement structure for future phases of design. The impacts of climate change on 200-year peak discharge of 255 m^3/s should be adopted as the design discharge for the replacement structure for future phases of design. The impacts of climate change on 200-year hydraulics are noted in the table above.

For a more complete discussion of the results, please refer to NHC’s 2017 report entitled: “Report on the 2016 Flood Event and Regional Hydrology.”

Reference

BC Ministry of Transportation and Infrastructure (BCMoTI). 2017. Commotion Creek Culvert, Structure No. 07037 Hydrotechnical Assessment and Design Report for 2016 South Peace Flood Recovery. MOTI Project 35478. (Report prepared by Northwest Hydraulic Consultants Ltd. for the BCMoTI). Victoria, BC: Province of BC. [accessed: 2019 Jul 03]. https://www2.gov.bc.ca/assets/gov/driving-and-transportation/transportation-infrastructure/contracting-with-the-province/documents/archive-unoffical-tender-documents-90-days/35478-0000/t3-7 commotion-creek-hydrotechnical-design-report-2017.pdf.

B.2 COASTAL FLEXIBLE DESIGN EXAMPLE: CAUSEWAY ELEVATION IN CONSIDERATION OF YEAR 2100 AND 2200 SEA LEVELS

Contributor: Eric Morris, P.Eng., M.A.Sc., Kerr Wood Leidal Associates Ltd. (KWL)

Problem Statement

Determine the minimum elevation for a new two-lane causeway to be constructed adjacent to the sea. A risk assessment has determined that the causeway is vulnerable to sea level rise and changes in wind and atmospheric pressure conditions. Design elevation to be appropriate for projected sea levels and climate to the year 2100 and to include flexible design to allow for climate adaptation to the year 2200. This example considers only wind-generated waves. Tsunami waves (earthquake and landslide generated waves) should also be considered where appropriate.

Approach

1. Minimum causeway elevation is calculated according to the methodology outlined in the BC Ministry of Forests, Lands and Natural Resource Operations' *Flood Hazard Area Land Use Management Guidelines* (referred to in this appendix as "the guidelines"). Note that the guidelines are intended as a tool to make land use decisions within flood hazard areas, and are not intended as a tool to design roads, but they do specify a risk level for flooding. Only the Flood Construction Level (FCL) provisions have been used to design the causeway; the building setback provisions have not been applied.
2. Obtain the latest provincial policy sea level rise projections from the guidelines.
3. Obtain climate projections from a climate specialist. In this particular example, wind and atmospheric pressure conditions are not projected to change at the project site. Sea level is the only climate parameter that is expected to change.
4. Estimate the existing 1:200 Year Annual Exceedance Probability (AEP) water level through probabilistic analyses of measured water level data and predicted tide data. Adjust data for local effects (e.g., wind set-up) as required. Note that according to the guidelines, a 1:200 AEP event is the minimum provincial standard for flood protection, but a more stringent criteria can be adopted if deemed appropriate.
5. Obtain ground uplift/subsidence data from Natural Resources Canada, Geodetic Survey Division. Note that potential causeway settlement should be considered. In this example, the causeway is expected to rise due to tectonic uplift.
6. Estimate deep water wave conditions though wave hindcasting based on wind data. Determine nearshore wave conditions, considering appropriate wave transformations. Calculate the wave run-up height for the design causeway slope and armouring. Note that in this case, the wave run-up/height does not change with water level (the wave run-up elevation changes with water levels, but the magnitude of the wave run-up itself does not change). Another approach for this design would be to use target wave over-topping rates rather than wave run-up heights.
7. Calculate the FCL for the year 2100 and 2200 and determine the required causeway elevation and width to allow the causeway to be raised for sea level rise adaptation to the year 2200.

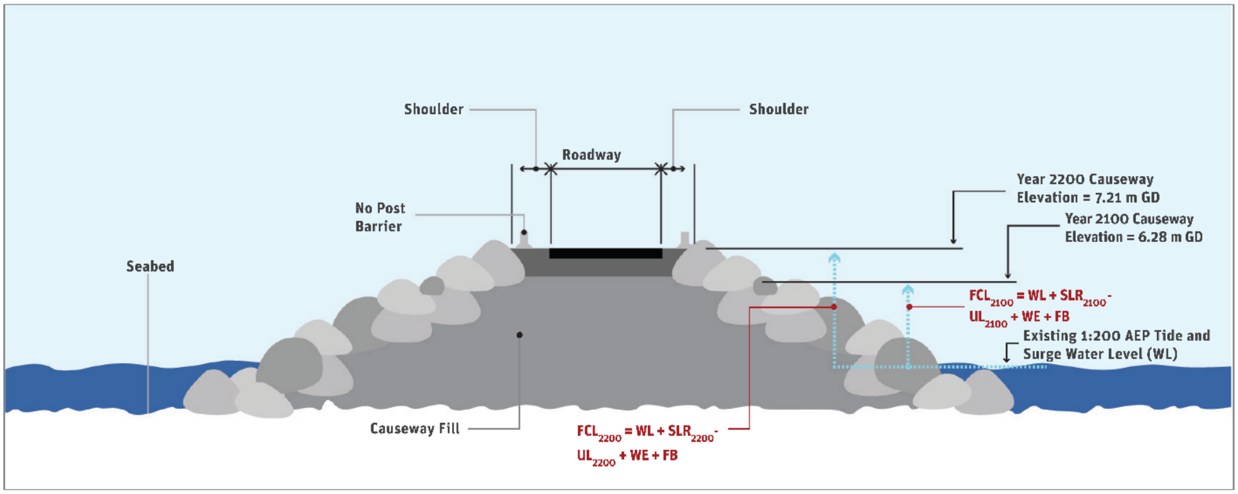

Figure B.2.1: Causeway cross-section showing year 2100 and 2200 elevations

DESIGN CRITERIA	
WATER LEVEL	
1:200 Year Annual Exceedance Probability (AEP) water level as determined through probabilistic analyses of tides and storm surge (WL)	2.74 m Geodetic Datum (GD)
SEA LEVEL RISE	
Allowance for Sea Level Rise to the Year 2100 (SLR_{2100})	1.0 m
Allowance for Sea Level Rise to the Year 2200 (SLR_{2200})	2.0 m
GROUND UPLIFT/SUBSIDENCE	
Ground Uplift to the Year 2100 (UL_{2100})	+0.06 m
Ground Uplift to the Year 2200 (UL_{2200})	+0.13 m
ESTIMATED WAVE EFFECTS ASSOCIATED WITH THE DESIGNATED STORM WITH AN AEP OF 1:200	
Wave run-up elevation exceeded by only 2% of the waves ($R_{2\%}$) (WE)	2.0 m
FREEBOARD	
Freeboard allowance (FB)	0.6 m

NOTE:
In general, wave effects may change over time with a changing climate, but in this example, they do not.

Calculations

Year 2100 FCL and causeway elevation:

$FCL_{2100} = WL + SLR_{2100} - UL_{2100} + WE + FB$

FCL_{2100} = 2.74 m GD + 1.0 m − 0.06 m+ + 2.0 m + 0.6 m

FCL_{2100} = 6.28 m GD

Year 2200 FCL and causeway elevation:

$FCL_{2200} = WL + SLR_{2200} - UL_{2200} + WE + FB$

FCL_{2200} = 2.74 m GD + 2.0 m − 0.13 m+ + 2.0 m + 0.6 m

FCL_{2200} = 7.21 m GD

Reference

British Columbia (BC) Ministry of Forests, Lands and Natural Resource Operations. 2018, Flood Hazard Area Land Use Management Guidelines, Amendment to Section 3.5 (The Sea) and 3.6 (Areas Protected by Dikes) of the guidelines (effective January 1, 2018). Victoria, BC: Province of BC. [accessed: 2019 Jul 3]. https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/integrated-flood-hazard-mgmt/final_amendment_to_s_35_and_36_fhalumg_17-10-01.pdf

B.3 AN APPROACH TO FLOOD HAZARD ASSESSMENT FOR SMALL WATERSHEDS: ASSESSMENT FOR THE CITY OF SURREY ACCOUNTING FOR PROJECTED CLIMATE CHANGE

Contributor: Monica Mannerström, P.Eng., Malcolm Leytham, Vanessa O'Connor, P.Eng., and Mariza Costa-Cabral, Northwest Hydraulic Consultants Ltd. (NHC)

Problem Statement

The City of Surrey is located on the south coast of British Columbia, just south of the City of Vancouver and north of the Canada/USA border. The greater part of the city is drained by the Serpentine and Nicomekl Rivers. These rivers, with a combined drainage area of about 300 km^2, originate in rolling uplands that have been heavily developed for residential and commercial use. The rivers then flow through flat, low-lying agricultural land to discharge into the Strait of Georgia and the Pacific Ocean. The lowland reaches of both rivers are extensively diked and their flood protection and drainage systems incorporate some 30 pump stations, 170 flap-gated culverts, and a complex network of flow storage areas, canals, ditches and spillways. At their outlets, the rivers drain into the ocean through flap-gated control structures ("sea dams"), with a sea dike protecting the flood plain from ocean flooding (Figure B.3 - 1).

Flooding of the agricultural lowlands of the two rivers is typically the result of heavy rain or rain-on-snow events, in combination with high ocean tides and storm surge. Sea level rise and increased runoff associated with climate change are expected to have a significant impact on the Serpentine and Nicomekl basins in terms of floodplain extents and the adequacy of the existing flood protection and drainage infrastructure. Of particular concern is the increased risk of flooding at the lowland/upland interface, where relatively modest increases in flood level could have a significant impact on residential and commercial properties.

Approach

The City of Surrey developed a scope of work to be conducted in two phases. In the first phase, completed in 2012, analysis of the impacts of climate change focused on the effects of projected sea level rise on flood risk and the infrastructure improvements required to ensure a 200-year level of protection from flooding in the year 2100. The second phase of work, completed in 2014, incorporated projected changes in rainfall regime under climate change scenarios.

Inundation of the Serpentine/Nicomekl River floodplain is a function of:

- the volume and temporal distribution of storm rainfall and the watershed's hydrologic response to rainfall;
- the time-varying sea level at the river outlets coincident with the storm event; and
- the hydraulic response of the system (comprising floodplain storage and the various hydraulic infrastructure) to the hydrologic inputs and the sea level boundary condition.

This complex system cannot be analyzed directly by statistical means and conventional storm event analysis; that is, it is not possible to state a priori what combination of sea level conditions and storm rainfall event will result in flood depths and inundation extent having an annual exceedance probability (AEP) of 0.5% (return period of 200 years).

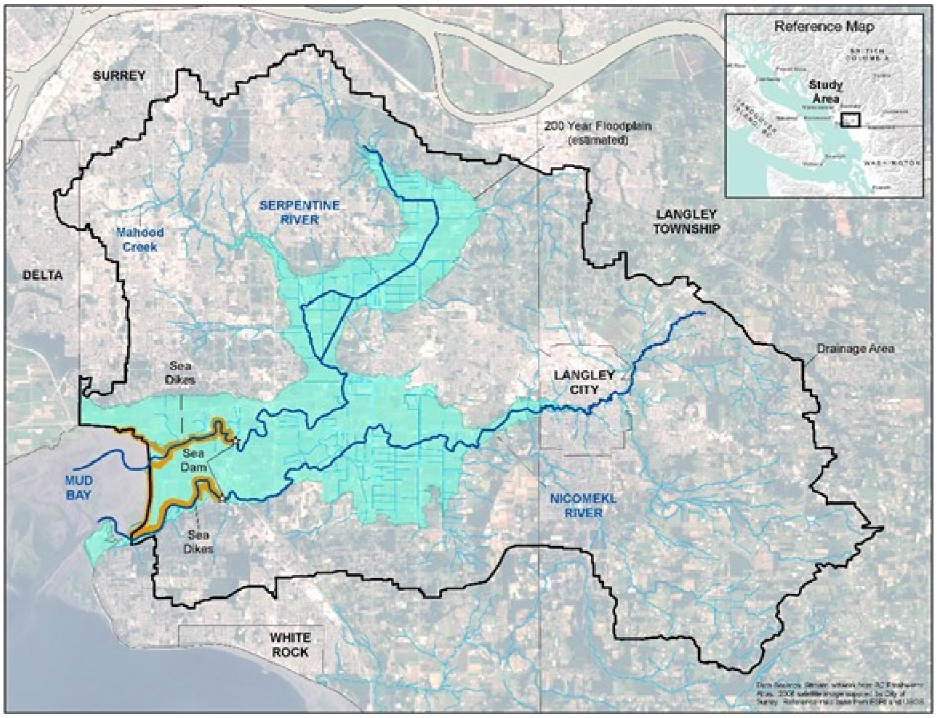

Figure B.3 - 1: Serpentine and Nicomekl Watersheds

To avoid the difficulties of a direct statistical joint probability analysis, a continuous simulation approach was adopted whereby long-term (approximately 50-year) simulations of the system's hydraulic performance were conducted, and the simulated annual peak floodplain water levels were subjected to conventional frequency analysis. The approach involved the following steps:

1. An approximately 50-year time series of historic hourly rainfall data was assembled and used as input to an HSPF hydrologic model to produce 50-year time series of simulated hourly runoff under current (nominally year 2010) land use conditions.
2. A hindcasting approach involving reconstruction of historic tide records and numerical modelling of historic storm surge and wind setup was used to develop hourly time series of ocean water levels for the same approximately 50-year time period.
3. The runoff and ocean level time series were then used as boundary conditions for a HEC-RAS hydraulic model of the river and floodplain system, to produce 50-year time series of simulated water levels at selected floodplain locations.
4. Annual maximum water levels at key locations were extracted from the hydraulic model results. These were analyzed through conventional frequency analysis to estimate 200-year (0.5% AEP) floodplain water levels representative of current (year 2010) conditions.

Once simulation of current (year 2010) conditions was complete, floodplain water levels representative of the year 2100 were estimated as follows:

1. Hourly time series of projected precipitation, representing two contrasting future climate scenarios, covering the 21st century, were developed for this study, to be used as input ("forcing") to our calibrated HSPF hydrologic model, in step 6. The projected precipitation time series were developed to be consistent, in a

statistical sense, with specific global climate model (GCM) runs, in what concerns daily intensity, storm duration, and the clustering in time of the highest-intensity episodes. The GCM runs of interest were selected from the most recent runs that served as the basis for the recent IPCC (2014) Fifth Assessment Report (i.e., the CMIP5 climate projections). We used GCM precipitation projections downscaled by the Pacific Climate Impacts Consortium (PCIC). Data from 12 GCMs are available from PCIC, and our first step was to analyze their downscaled results. Nearly all of the 12 GCMs project future increases in daily precipitation intensity accompanied by declines in the mean number of precipitation days in a year. The second step consisted in selecting two appropriate GCM runs. It was desired to identify which GCM runs represent, in the context of all PCIC projections, a "severe scenario" and a "moderately high scenario" in terms of flooding risk. The third step consisted in altering the observed historical time series of hourly precipitation at the Surrey Municipal Hall gauge, so as to create the two projected hourly time series. To create each future precipitation time series, the observed historical time series was modified as follows.

2. Precipitation days were removed at random from the observed time series, until the desired number, consistent with the GCM projections, was reached. The daily precipitation totals on the remaining wet days were then increased, so that the distribution of daily precipitation on wet days would be consistent with the GCM projected increases. To this end, the return period of each daily observed precipitation value was estimated, and the value was then replaced by a higher value having that same return period in the future distribution. To estimate return periods for the largest daily precipitation values, a generalized extreme-value distribution (GEV) was fitted to each data set, using a peaks over threshold (POT) methodology (Coles 2001).
3. The HSPF hydrologic model was modified to reflect projected future (year 2100) land use, and produce time series of projected runoff. In the first phase of work, future rainfall input was assumed to be unchanged from the historic record. In the second phase, the projected rainfall time series developed in step 5 were used.
4. A relative sea level time series representative of the year 2100 was developed, considering the effects of absolute sea level rise and land subsidence. Provincial guidelines (Ausenco Sandwell, 2011) call for an assumed 1 metre absolute sea level rise between 2000 and 2100. The observed sea level rise from 2000 to 2010 was approximately 0.03 m. We therefore assumed a further 0.97 m of absolute sea level rise from 2010 to 2100. Land subsidence was estimated from historic observations at 2.5 mm/year. The net effect of absolute sea level rise and land subsidence results in a relative sea level rise of about 1.2 m from 2010 to 2100. This adjustment was applied to the historic sea level time series from step 2 to represent conditions in 2100.
5. Steps 3 and 4 were repeated using the runoff and ocean level time series for year 2100 to produce revised 200-year floodplain water levels with climate change (sea level rise and rainfall changes).

Results

The following results stem only from the projected rise in mean sea level and changes in land use, but do not yet consider projected changes in precipitation or temperature. Compared to 2010 conditions, the 200-year flood level is expected to increase by 0.9 to 1 m on the approximately 12 km reach of the Nicomekl River upstream from the sea dam. For the approximately 14 km reach of the Serpentine River upstream from its sea dam, the 200-year flood level will increase by about 0.7 m. Further upstream, the flood level increases taper off to 0.1 m, due solely to the impacts of land-use change on peak flows. Floodplain storage cells will see 200-year water level increases ranging from 0.1 to 0.4 m. The modelling assumed that all dikes and the sea dam structures would be raised to prevent overtopping.

In response to the assumed 1-metre sea level rise (per provincial guidelines), the return period for particular flood levels will change greatly. Water levels with a current 72-year return period will on average occur annually by the year 2100. Similarly, the existing 200-year flood level will have an estimated return period of less than two years.

The continuous simulation approach adopted for this work provides a number of significant advantages over traditional event analysis:

- It explicitly captures the joint occurrence of extreme sea levels and severe rainfall events.
- It explicitly accounts for varying duration and amounts of rainfall (and runoff) and the matching of the rainfall with the sea level regime.
- It captures the shift in significance of longer lower-intensity rainfall events under conditions of sea level rise. (Higher sea level implies that longer-duration rainfall events become more important in defining interior flood levels, since the sea dams are closed for longer periods of time)
- It avoids arbitrary assumptions about the coincidence or lack of coincidence of individual factors that would be required if a direct statistical analysis were attempted.

The information developed provides a necessary first step in understanding the system's response to climate change and the infrastructure improvement that may be necessary to manage future flood risk. The information is, however, subject to large and unquantifiable uncertainty, due to unknown future emissions of greenhouse gases, uncertain response of the global climate system to the atmospheric accumulation of those gases, and incomplete understanding of regional manifestations from such global changes (e.g., Hawkins and Sutton 2010; Kundewicz et al. 2013). Additionally, precipitation processes are very complex and difficult to simulate accurately in models. The downscaling, in space and time, of GCM-projected climate variables, the extrapolation of frequency analyses to long return periods, and the disaggregation of projected daily precipitation to hourly represent additional sources of uncertainty. The sea level and precipitation projections developed in this work should be considered to be plausible representations of future conditions, given the best current scientific information, and do not represent specific predictions. The actual future realizations of precipitation at Surrey will differ from any of these scenarios.

References

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B.4 CLIMATE CHANGE RISK ASSESSMENT OF A SMALL INFRASTRUCTURE PROJECT: STORM SEWER IN CITY X

Contributor/Reviewer: Julia Stafford, P. Eng., Climate Change Engineer, WSP Global Inc.

Introduction

This example prepared by Engineers and Geoscientists BC serves to illustrate how the principles outlined in the *Professional Practice Guidelines – Developing Climate Change-Resilient Designs for Highway Infrastructure in British Columbia* apply to small infrastructure projects. The consideration of climate change and extreme weather events in this example is appropriate to the small scale of the project and would allow an Engineer of Record (EOR) to complete the British Columbia (BC) Ministry of Transportation and Infrastructure (BCMoTI) Design Criteria Sheet for Climate Change Resilience contained in Technical Circular T-04/19, Climate Change and Extreme Weather Event Preparedness and Resilience in Engineering Infrastructure Design (BCMoTI 2019).

Project Description

City X is located in a remote location in BC. The scope of the project was limited to designing a stormwater pipe to convey the five-year design flow from a site with the following design parameters for a 50-year infrastructure design life:

- Landscaped area (C=0.20) = 1.00 ha (where C is the proportion of impervious area)
- Parking area (C=0.95) = 0.50 ha
- Time of concentration = 10 min for the area, and the pipe is concrete at 2% slope

Given the limited scope of this project, the rainfall intensity was the single climate parameter considered for representative concentration pathway (RCP) 2.6, RCP 4.5, and RCP 8.5, using version 3.5 of the IDF CC tool developed by the University of Western Ontario (2018). The choice of RCP scenario that was used was discussed with the client and based on professional judgment. In general, RCP 8.5, emission scenario should global GHG emissions not be reduced, is chosen conservatively as there is great uncertainty of future emissions. It is good practice to complete sensitivity analyses on all three RCP scenarios as a means of comparison, to determine the appropriate level of tolerance for the client.

Climate Change Risk Assessment

Adapting methods used in the City of Barrie's Storm Drainage and Stormwater Management Policies and Design Guidelines (City of Barrie 2017), the following equations were applied to calculate flows, pipe diameters from intensity rates generated using the IDF CC tool:

Composite Runoff Coefficient = $\frac{\Sigma(Area_i)(Coefficient_i)}{Total\ Area}$

$$i = \frac{A}{(t_d + B)^C}$$

$$Q = \frac{(C)(i)(A)}{360}$$

Using n=0.013, the following pipe flow equation calculates the pipe diameter:

$$Q = \left[\frac{0.312}{n}\right](D)^{\frac{8}{3}}(S)^{\frac{1}{2}}$$

The full flow velocity was determined using the following equations:

$$V_{full} = \frac{Q_{full}}{A}$$

$$Q_{capcity} = Q_{full}$$

The following climate models were selected in the IDF CC tool, as they are used by the Pacific Climate Impacts Consortium (2019) in the region of western North America: CanESM2, CCSM4, CNRM-CM5, CSIRO-Mk3-6-0, GFDL-ESM2G, HadGEM2-ES, MIROC5, MRI-CGCM3 and MPI-ESM-LR. The sensitivity analysis could be derived from any combination of models or bias or non-bias corrected. The EOR should use professional judgment to determine which model is most appropriate to meet specific requirements of the storm sewer in City X. An “all model ensemble” is an option averaging the results across all models in the tool.

IDF data was projected under the RCP 2.6, RCP 4.5, and RCP 8.5 climate scenarios from 2045 to 2095 for a 50-year infrastructure design. For the future climate scenarios, the intensity, flow, and pipe diameter were calculated for each of the mentioned models and then averaged across the models. Should the design life of the infrastructure extend beyond 2070, the IDF projections set from 2045 to 2095 would not be accurate and could result in potentially underestimating future rainfall. The values for rainfall intensity, flow, and pipe diameter calculated using historical IDF curves and IDF curves under climate change are shown in Table B.4.1 below.

Recommendation

The actual pipe diameter is 0.381 m and, as shown in Table B.4.1 above, current rainfall intensities have already exceeded the capacity of the current pipe. The owner of the storm sewer should upsize their infrastructure to meet the demands of projected future rainfall. IDF CC models under RCP 2.6, RCP 4.5, and RCP 8.5 have consistently indicated a 50 mm increase in pipe size to accommodate flows across a range of future projections in rainfall intensities. It should be noted that consistent flow projections across all RCPs provides the owner greater confidence and need to upsize to improve resilience in a 50-year infrastructure design.

Table B.4 - 1: Rainfall Intensity, Flows and Pipe Diameter Required under Current Climate Conditions and under Representative Concentration Pathway (RCP) 2.6, RCP 4.5, and RCP 8.5 Scenarios

	HISTORICAL IDF DATA	IDF CC RCP 2.6 DATA	IDF CC RCP 4.5 DATA	IDF CC RCP 8.5 DATA
Rainfall intensity (mm/hr)*	151.2	206.9	213.5	212.8
Flows (m^3/s)	0.284	0.388	0.400	0.399
Pipe diameter required (mm)	394	443	449	448
Nominal pipe diameter (mm)	450	450	450	450

*An alternative strategy is to estimate the percent change between the IDF data for a climate scenario and historical climate data, averaged over the appropriate return period. This percent change can then be applied to the historical rainfall to arrive at an updated value.

Discussion

There are a number of factors to consider when using the data produced by the IDF CC tool to inform the design of the storm sewer. Among these are the inherent uncertainties in statistical downscaling from global climate models. Statistical downscaling requires developing a mathematical relationship between historically observed data and processed GCM outputs. The IDF CC tool relies on the input from historical data, and if the input data is incomplete, the downscaled output will not be fully representative of actual conditions. For example, some climate stations in BC only have processed data up to 2001, which does not include the most recent 20-year period in which changes in climate have occurred prior to the present day. The IDF CC method only truly applies to rainfall-dominated watersheds, and preferably other methods should be used for predicting design flows in snowmelt-dominated watersheds. Of relevance to the mountainous regions of BC, a recent Canadian study (Martel et al. 2020) found that topography—or variations in a region's elevated terrain—plays an important role in the type, amount, intensity, and duration of precipitation events. Results of the study showed that high-altitude regions are expected to experience the greatest increase in extreme event frequency (about 4 to 5 times more frequent) by the end of the century (relative to ~2000), specifically for short duration (1 hour) events. The engineer should communicate to the client(s) that this is an oversimplified approach to estimating design flows, and values should be treated as an estimate rather than an exact value with respect to climate change.

Although the conclusion reached for this small infrastructure project was no changes to the storm sewer design, it is important that the IDF curves under projected climate change scenarios are considered in the design process in BCMoTI projects. As outlined in a study conducted by the Town of Creston, due to the high cost of overdesigning pipe diameter, alternative approaches that focus on runoff detention, temporary storage, infiltration, and runoff may be considered (Paré 2015). Alternative approaches that may be used include redirecting runoff water into swales, sand filters, detention ponds, and wetlands. It should be noted that the performance of the design will only be assured with proper inspection and maintenance of the storm sewer during its service life. Regular inspection will detect any debris or vegetation that may block or partially block the conveyance of water through the sewer, thus not allowing it to perform as designed.

Engineers currently face challenges in understanding projected climate data and incorporating it into their design of public infrastructure. To facilitate the use of projected climate data in design, the BCMoTI is working with the Pacific Climate Impacts Consortium to develop climate data that engineers can use in their design of public infrastructure.

References

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B.5 TOWN OF CRESTON: SOUTHEAST DRAINAGE BASIN STUDY – EXECUTIVE SUMMARY

Contributor: Julia Wansbrough, M.Sc, EIT, Ghislaine Miliu, EIT, Ben Worth P.Eng., Elise Paré, P.Eng.

Problem Statement

WSP were retained by the Town of Creston to undertake the Southeast Drainage Basin Study, to investigate the current and future (climate change-influenced) performance of the storm drainage infrastructure system within the study area, and provide a report to serve as the basis for future decisions on investments in storm drainage infrastructure in the area. The study area consisted of around 32 ha of developed land within the Town limits (primarily single-lot residential), as well as two relatively large external undeveloped catchments to the south (5.9 ha and 16.3 ha, respectively) which currently drain through the Town's storm-drainage systems.

Approach

Following a data collection process, a hydrologic and hydraulic (H&H) model was developed for the study area (using EPA SWMM software) to simulate performance of the existing system under a range of return periods. A series of climate change-impacted scenarios were also tested (2020s, 2050s, and 2080s) using modified IDF parameters for the Representative Concentration Pathway (RCP) 8.5 trajectory. These IDF parameters had been developed previously, according to the Development of IDF Curves under a Changing Climate assignment (Paré 2015).

As part of the climate change impact assessment, a sensitivity analysis was also undertaken to quantify the impact of "rain on frozen ground" (ROFG) events in the catchment. These were considered in response to local observations related to timing of storm events in the Town (noting that in recent years heavy rainfall events were starting to happen earlier in the calendar year when there was still snow cover on the ground, and as a result, runoff volumes during these storm events were increased). Several modelling approaches were considered for this analysis; however, it was concluded that the most efficient way of testing the impact was simply to increase the percentage imperviousness of the sub-catchments to increase the proportion of rainfall that is converted to runoff in the model. It was concluded that ROFG events had the potential to significantly increase peak flows in the system, and should therefore be considered in any future upgrade decisions.

Results

The existing conditions analysis indicated that the system was generally undersized in terms of conveyance capacity, and had the potential to flood in certain areas even during smaller (i.e., 5-year or 10-year) design events. Issues associated with lack of conveyance capacity are exacerbated by additional flow draining through the system from the external upstream catchments, and the anticipated hydraulic performance deteriorates even further under future climate change impacted rainfall events.

A series of conceptual servicing alternatives were developed and evaluated to decrease flood risk, and improve level of service offered by the drainage infrastructure.

Alternatives considered fell within the following categories:

a) Onsite detention and/or increased capacity
b) Diversion to alternate discharge point
c) Offsite detention

Each alternative was simulated using the H&H model and results were compared to determine relative effectiveness from a technical perspective. Cost estimates of the feasible options were also produced in order to inform decision making. Model results indicated that the larger scale interventions—that is, options (b) and (c), involving detention and/or re-routing of external drainage areas away from the Town drainage system—were the only options that had a significant impact on performance. On that basis, it was recommended that a more detailed feasibility study be undertaken on the more cost-effective of these two options, which was option (c).

References

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B.6 A SUMMARY OF PIEVC RISK ASSESSMENTS CONDUCTED BY THE BC MINISTRY OF TRANSPORTATION AND INFRASTRUCTURE

Contributor: Dirk Nyland, P.Eng., IRP, BC Ministry of Transportation and Infrastructure

Introduction

To date, the British Columbia (BC) Ministry of Transportation and Infrastructure (BCMoTI) has applied the Public Infrastructure Engineering Vulnerability Committee (PIEVC) Engineering Protocol when conducting a Climate Change Risk Assessment of a number of highways and highway segments. This appendix summarizes the climate parameters and infrastructure components assessed for the following highways and highway segments:

- Coquihalla Highway – Hope to Merritt section
- Yellowhead Highway 16
- Highway 20 in the Bella Coola Region
- Highway 37A in the Stewart (Bear Pass) Region
- Highway 97 in the Pine Pass Region

In 2010, the BCMoTI applied the PIEVC Engineering Protocol to identify components of the Coquihalla Highway Merritt South Road Section that were at risk of failure, loss of service, damage, or deterioration due to the impacts of climate change (BCMoTI and Nodelcorp 2010).

In 2011, the BCMoTI conducted a similar study for the Yellowhead Highway. In this study, the BCMoTI applied the PIEVC Engineering Protocol to develop future climate risk profiles of transportation and infrastructure on a section of the Yellowhead Highway and analyzed components with high risk elements (BCMoTI and Nodelcorp 2011)

In 2014, the BCMoTI applied the lessons learned from the Coquihalla and Yellowhead highway studies, to conduct an engineering vulnerability assessment of three highway segments. Using the PIEVC Engineering Protocol, the BCMoTI identified components at risk of failure, loss of service, or damage in two coastal highway segments—Highway 20 in the Bella Coola region and Highway 37A in the Stewart (Bear Pass) region—and one Interior highway segment—Highway 97 in the Pine Pass region (BCMoTI et al. 2014).

Summary of Infrastructure Component-Climate Parameter Interactions

As illustrated by Table B.6 - 1, there is variation in the infrastructure component–climate parameter interactions that each study examined. The table serves as a summary of the PIEVC Engineering Protocol risk assessments conducted by the BCMoTI.

The full reports can be accessed either through the links in the list of references below or in the "Adaptation Case Studies" section of the Engineers and Geoscientists BC Climate Change Information Portal (available online at: egbc.ca/Practice-Resources/Climate/Climate-Change-Information-Portal).

Table B.6 - 1: Summary of Infrastructure Component-Climate Parameter Interactions Examined in BCMoTI Studies

This table summarizes the infrastructure component–climate parameter interactions that have been examined in BCMoTI PIEVC Engineering Protocol risk assessment studies. Interactions marked with a “C” were examined in the Coquihalla Highway study, interactions marked with a “Y” were examined in the Yellowhead Highway study, interactions marked with a “BC” were examined in the Bella Coola study, interactions marked with an “S” were examined in the Stewart study, and with a “PP” were examined in the Pine Pass study. Interactions marked with “All” were examined in all of the studies listed.

INFRASTRUCTURE COMPONENTS	HIGH TEMPERATURE	LOW TEMPERATURE	AVERAGE TEMPERATURE	TEMPERATURE VARIABILITY	FREEZE/THAW	FROST PENETRATION	FROST	TOTAL ANNUAL RAINFALL	EXTREME HIGH RAINFALL	LIGHT SUBSTANTIAL RAINFALL	HEAVIER SUBSTANTIAL	SUSTAINED RAINFALL	SNOW (FREQUENCY)	SNOW ACCUMULATION	RAIN ON SNOW	FREEZING RAIN	RAIN ON FROZEN GROUND	SNOW STORM/BLIZZARD	RAPID SNOW MELT	SNOWMELT DRIVEN PEAK FLOW EVENTS	MAGNITUDE OF STORM DRIVEN PEAK	FREQUENCY OF STORM DRIVEN PEAK	HIGH WIND/DOWNBURST	HAIL/SLEET	GROUND FREEZING	ICE/ICE JAMS
Surface – Asphalt	C,Y	C,Y		C	C,Y	C	C		C				C	C		C		C			C	C			Y	
Pavement Marking	C,Y	C,Y		C	C,Y								C	C		C		C								
Shoulders (including gravel)	Y				Y				All	BC, S,PP	BC, S, PP	Y	BC, S, PP, C	BC, S, PP, C		C		C		PP	BC, S, PP, C	S, PP, C				
Barriers					C				Y				C	C				C								
Curb	C,Y	Y			C,Y				Y				BC,C, PP,	C												
Luminaires													C	C		C	Y	C					Y			
Poles						Y							C	C		C	Y						Y			
Signage						C,Y							C	C		C	Y	C					Y			
Ditches				C	C,Y			Y	All	BC, S, PP	BC, S, PP	Y	BC,C, SS, PP,	BC, S, PP, C	All		S	C	BC, S, PP, Y	BC, S, PP	BC, S, PP, C	BC, S, PP, C				S
Embankments / cuts	Y			C	C,Y	C	C	BC, S, PP, Y	All	BC, S, PP	BC, S, PP	Y	C	BC, S, PP, C	BC, S, PP, Y		S	C	BC, S, PP, Y	BC, S, PP	BC, S, PP, C	BC, S, PP, C				S
Hillsides	Y			C	C,Y			BC, S, PP, Y	All	BC, S, PP	BC, S, PP	Y	C	BC, S, PP, C	All		S		BC, S, PP, Y	BC, S, PP	BC, S, PP, C	BC, S, PP, C				S
Protection Works/Armoring								BC, SS, PP	BC, S, PP	BC, S, PP	BC, S, PP			BC, S, PP	BC, S, PP		S		BC, S, PP	BC, S, PP	BC, S, PP	BC, S, PP				BC, S, PP
Engineered Stabilization Works					C	C	C	BC, S, PP	S, C					BC, S, PP	S		S		BC, S, PP	BC, S, PP	BC, S, PP, C	BC, S, PP, C				S
Avalanche (Inc Protections Works)		C		C	C	C	C		C				C	C	C	C		C			C	C				

INFRASTRUCTURE COMPONENTS	HIGH TEMPERATURE	LOW TEMPERATURE	AVERAGE TEMPERATURE	TEMPERATURE VARIABILITY	FREEZE/THAW	FROST PENETRATION	FROST	TOTAL ANNUAL RAINFALL	EXTREME HIGH RAINFALL	LIGHT SUBSTANTIAL RAINFALL	HEAVIER SUBSTANTIAL	SUSTAINED RAINFALL	SNOW (FREQUENCY)	SNOW ACCUMULATION	RAIN ON SNOW	FREEZING RAIN	RAIN ON FROZEN GROUND	SNOW STORM/BLIZZARD	RAPID SNOW MELT	SNOWMELT DRIVEN PEAK FLOW EVENTS	MAGNITUDE OF STORM DRIVEN PEAK	FREQUENCY OF STORM DRIVEN PEAK	HIGH WIND/DOWNBURST	HAIL/SLEET	GROUND FREEZING	ICE/ ICE JAMS
Debris Torrents (Inc Protection Works)	C			C	C	C	C		C				C	C	C						C	C				
Structures that Cross Streams	C,Y	C,Y		C	C,Y	C,Y	C	Y	All		PP	Y			BC, S, PP, Y	C	S, Y		BC, S, PP, Y	BC, S, PP, Y	BC, S, PP, C	BC, S, PP, C	Y			BC, S, PP, Y
Structures that Cross Roads	C,Y	C,Y		C	C,Y	C,Y	C		C, Y			Y			Y	C	Y				C	C	Y			
MSE Walls /Retaining Walls					C				S						S		S		S	S	C	C				S
Road Sub-Base											PP										BC,PP	BC,PP				
River Training Works (Rip Rap)		C		C				Y	C,Y			Y							Y	Y	C	C				Y
Pavement Structure		C		C,Y	C,Y	C,Y	C	Y				Y													Y	
Detail Drainage																					S	S				
Drainage Appliances					C,Y	C		Y	PP, C,Y		PP	Y		C	PP, C,Y	C	Y		Y	PP	C			Y		
Sub Drains		C,Y			C,Y	C	C	Y	C,Y			Y			Y						C					
Catch Basins				Y	C	C		Y	PP, C,Y		PP	Y		C	PP, C,Y	C	Y		Y		C	C		Y		
Grates																										
Culverts <3 meters		C,Y		C	C,Y			Y	All	BC, S, PP	BC, S, PP	Y			BC, S, PP, Y		BC, S, PP		BC, S, PP, Y	BC, S, PP, Y	BC, S, PP, C	BC, S, PP, C		Y		BC, S, PP, Y
Culverts > 3 meters		C,Y		C	C,Y			Y	All	BC, S, PP	BC, S, PP	Y			BC, S, PP, Y		BC, S, PP		BC, S, PP, Y	BC, S, PP, Y	BC, S, PP, C	BC, S, PP, C				BC, S, PP, Y
Asphalt Spillway and Associated Piping/Culvert	C,Y	C			C,Y			Y	C,Y			Y		C	C	C	Y		Y		C			Y		
Bridge End Fill									BC, S, PP		BC, S, PP				BC, S, PP				BC, PP	BC, S, PP	BC, S, PP	BC, S, PP				
3rd Party Utilities									PP, C,Y		PP					C	Y			PP	PP, C	PP				
Railway								Y	PP, Y		PP	Y			Y		Y		Y	PP, Y	PP	PP				

References

BCMoTI; Nodelcorp Consulting Inc.; Pacific Climate Impacts Consortium. 2014. Climate Change Engineering Vulnerability Assessment of Three British Columbia Highway Segments. Victoria, BC: Province of BC. [accessed: 2019 Jul 03]. www.th.gov.bc.ca/climate_action/documents/hwy20_bella_coola-hwy37A_Stewart-hwy97_Pine_Pass.pdf.

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BC Ministry of Transportation and Infrastructure (BCMoTI); Nodelcorp Consulting Inc. 2010. Climate Change Engineering Vulnerability Assessment: Coquihalla Highway (B.C. Highway 5) Between Nicolum River and Dry Gulch. Victoria, BC: Province of BC. [accessed: 2019 Jul 03]. http://pievc.ca/sites/default/files/coquihalla_highway_nicolum_river_and_dry_gulch_final_report_web.pdf.

B.7 STUDY OF THE IMPACTS OF CLIMATE CHANGE ON PRECIPITATION AND STORMWATER MANAGEMENT, METRO VANCOUVER [TECHNICAL BRIEF]

Contributor: Lillian Zaremba, P.Eng., Senior Project Engineer, Liquid Waste Services, Metro Vancouver

This Project addressed the following objectives:

- ☑ Update the existing IDF curves to present day
- ☑ Quantify uncertainty of climate change impacts on rainfall and develop future climate IDF curves
- ☑ Determine the potential effects of climate change on sewerage and stormwater infrastructure
- ☑ Develop good practice recommendations for incorporating climate change in infrastructure planning design

Background

Climate change adaptation is one of the most important issues facing local governments today. Increasing frequency and intensity of extreme rainfall events will have a significant impact on existing sewerage and stormwater collection infrastructure. Municipalities must adapt to changing rainfall regimes to ensure that adequate levels of service for infrastructure are maintained in the future.

Engineers, planners, and policy makers use Intensity-Duration- Frequency (IDF) curves in municipal planning and infrastructure design. IDF curves characterize the relationship between the intensity of rainfall occurring over a specified period and its frequency of occurrence. They are based on historical observations of rainfall. Developing future climate IDF curves is essential for planning for climate change.

Currently, there is no standard or accepted methodology to derive IDF curves for future climate conditions. The Greater Vancouver Sewerage and Drainage District (GVS&DD) initiated this project to advance the knowledge and capabilities of GVS&DD and its member municipalities to adapt to the effects of climate change within the region's sewerage and drainage infrastructure.

Existing Climate IDF Curves

The existing IDF curves for the Metro Vancouver region were updated. Rainfall data from 74 stations across the region were used to perform a regional rainfall frequency analysis (RRFA). IDF curves were developed for six homogeneous rainfall zones as shown in Figure B.7 - 1. A sample updated IDF curve is depicted in Figure B.7 - 2.

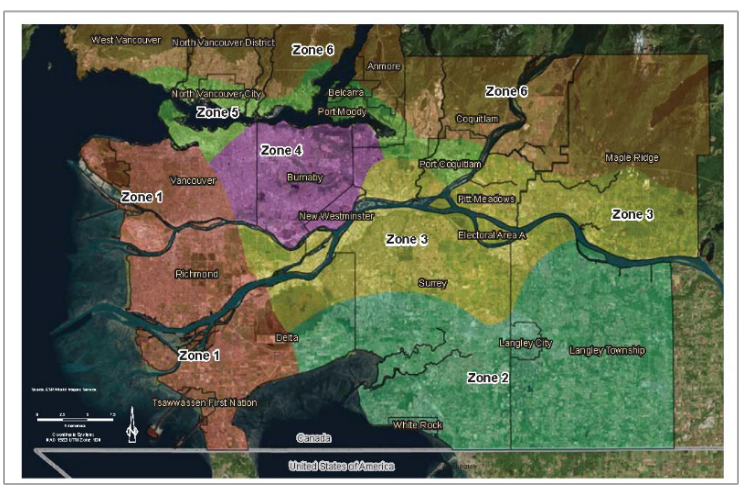

Figure B.7 - 1: Rainfall Zones

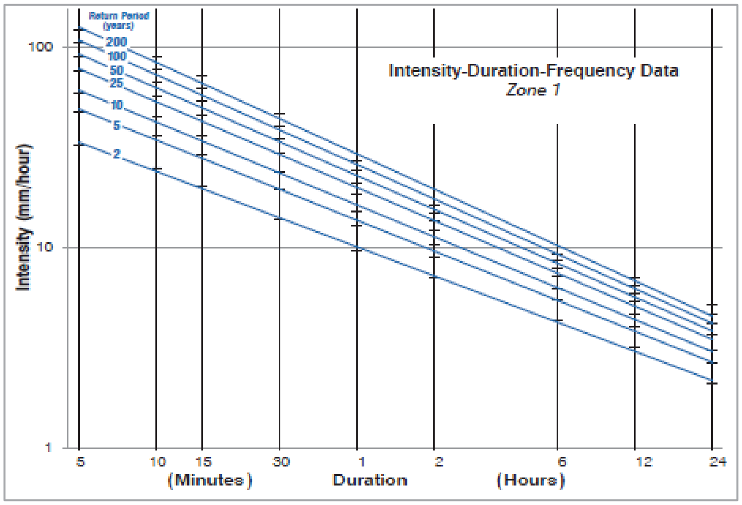

Figure B.7 - 2: Sample IDF Curve

Future Climate IDF Curves

Future climate IDF curves were developed from an ensemble of 12 Global Circulation Models (GCM). A new methodology was developed to address challenges in developing future climate rainfall events from GCM data. Projections of future precipitation are subject to many uncertainties in climate modelling, prediction of the future economy, population and technology, and other factors. A sensitivity analysis compared the relative importance of various sources of uncertainty by evaluating over 108,000 combinations of factors and their effects on IDF curves.

The results of the sensitivity analysis were used to define IDF curves for a moderate and a high climate change scenario. Both scenarios were based on the Representative Concentration Pathway (RCP) 8.5 "business- as-usual" greenhouse gas (GHG) emissions.

The moderate change IDF curve represents the median or likely increase in rainfall. The high change IDF represents an extreme or worst- case increase. Moderate and high change future IDF curves were developed for two time horizons, 2050 and 2100, as shown in Figure B.7 - 3.

All of the future IDF curves predict substantial increases in rainfall. The average increase for each future climate IDF curve is shown in Figure B.7 - 4. The increase for the high climate change scenario for 2050 is similar to the increase for the moderate climate change scenario for 2100. This indicates that a certain level of increase is expected to occur, but it is not certain when the increase will occur (i.e., it may occur by 2050 in the worst-case scenario, or it may be delayed to 2100 in the moderate scenario).

Figure B.7 - 3: Future Climate IDF Curves

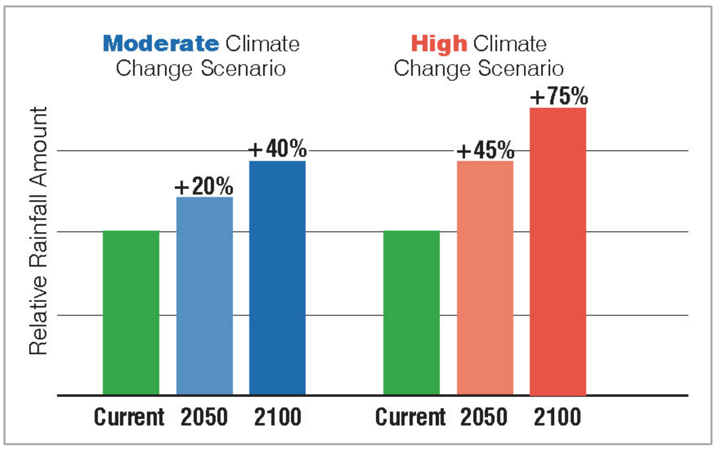

Figure B.7 - 4: Average Rainfall Increase

Potential Impacts on Infrastructure

The potential impacts of climate change on infrastructure were analyzed. Three case studies were examined: stormwater drainage networks, sewage collection systems, and combined sewer systems. Significant impacts were identified, and applying adaptation measures will require significant expense (Table B.7 - 1).

Increases in future rainfall due to climate change in combination with sea level rise could cause flooding in stormwater drainage networks. Adaptation measures are key to ensuring the levels of service of stormwater drainage infrastructure are maintained.

Climate change is expected to impact sewage collection systems through increasing rainfall derived inflow and infiltration (RDII). Population growth is also a significant factor for sewage collection systems. Adaptation measures are focused on reducing the impact of increased RDII.

More combined sewer overflows can be expected with increasing stormwater volume and RDII due to climate change. Population growth also affects the capacity of combined sewers. Along with the adaptation measures already described, accelerated sewer separation should also be considered.

Table B.7 - 1: Adaptation Measures for Stormwater and Sewage Collection

STORMWATER ADAPTATION MEASURES	SEWAGE COLLECTION ADAPTATION MEASURES
• Best management practices • Green Infrastructure/Low Impact Development • Peak flow diversion/storage • Stormwater management ponds • Pipe upsizing • Rehabilitation of infrastructure part-way through design life	• RDII reduction • Peak flow storage • Private-side measures (e.g. backflow preventors) • Pipe upsizing • Increases in the capacities of pump stations and wastewater treatment plants

Good Practice Recommendations

The future climate is uncertain, and climate change adaptation must balance the uncertainty with risk and the infrastructure planning horizon. Selecting the preferred IDF curve for planning and design is a key factor to ensure that the right adaptation measures are selected, at the right time, for the right reasons, and for the right costs. The selection of the preferred IDF curve for adaptation planning is based on the level of risk, as shown in Figure B.7.5.

Using the current climate IDF curves for design is suitable for temporary infrastructure (e.g., less than five-year design life). Using the moderate change future climate IDF curves is suitable for infrastructure with low to medium-risk due to failure. Using the high change future climate IDF curves is suitable for infrastructure where the risk due to failure is high or catastrophic. The selection of 2050 or 2100 depends on the planning horizon of the infrastructure.

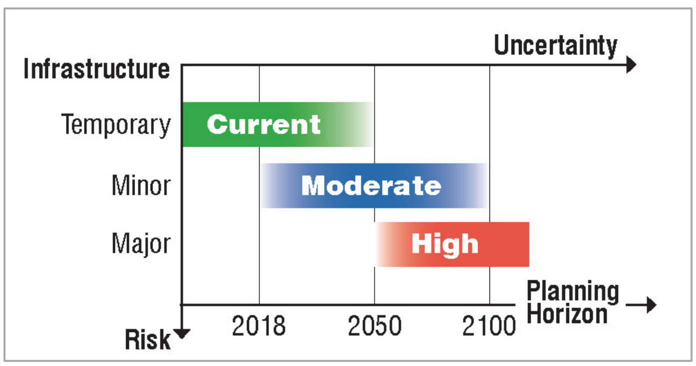

Figure B.7 - 5: Climate Change Adaptation

References

Metro Vancouver. 2018a. Study of the Impacts of Climate Change on Precipitation and Stormwater Management. August 2018. [Full Report]. Prepared by GHD for Metro Vancouver and the Greater Vancouver Sewerage and Drainage District (GVS&DD). Vancouver, BC: Metro Vancouver. [accessed: 2019 Apr 16]. http://www.metrovancouver.org/services/liquid-waste/drainage/stormwater-management/resources/Pages/default.aspx.

Metro Vancouver. 2018b. Study of the Impacts of Climate Change on Precipitation and Stormwater Management. [Technical Brief]. Prepared by GHD for Metro Vancouver and the GVS&DD. Vancouver, BC: Metro Vancouver. [accessed: 2019 Apr 16]. http://www.metrovancouver.org/services/liquid-waste/drainage/stormwater-management/resources/Pages/default.aspx.

B.8 GEOMORPHIC RISK ASSESSMENT CONSIDERATIONS

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This appendix is included to:

- raise awareness of fluvial and hillslope geomorphic hazards affecting highway stream crossings;
- qualify how climate change may be affecting such hazards in the future; and
- provide guidance on when to engage geomorphologists; i.e., professionals working as geotechnical engineers, geological engineers, engineering geologists, and (broadly) geoscientists with the appropriate training.

Introduction

Geomorphic risks, particularly those related to impact of debris floods and debris flows in steep creeks and alluvial fan locations, need to be managed appropriately in highway design and retrofit projects. "Steep" creeks are usually classified as those with a gradient exceeding 5%. Steep creeks are subject to so-called "hydrogeomorphic hazards" which encompass debris flows, debris floods, bank erosion, and scour. These processes are related and may change in intensity and type in space and time.

Type 1 debris floods (those initiated by exceedance of a critical shear stress to mobilize the largest particles) can occur on almost all gravel bed streams; debris flows occur preferentially on creeks with average slopes >25%. Geomorphic risks for stream crossings or highways along streams also need to consider debris flows entering upstream, where they can impound creeks or dilute into debris floods and lead to higher bulk densities, which facilitates bank erosion and sediment entrainment. Scour can lead to undermining of bridge foundations, piers, or culverts, while bank erosion can isolate bridges or culverts and erode highway embankments.

Many, though not all, geomorphic hazards are likely to increase in frequency and/or magnitude due to climate change, through changes in antecedent moisture and rainfall intensities and durations, attributed to a higher air moisture content, but also changes to the occurrence and intensity of extratropical storms or free-air convective storms. Higher order impacts will increasingly come from beetle infestations and increasingly severe wildfires, which change both the hydrology and sediment supply to creeks and rivers.

Considerations for the Engineer of Record

At a minimum, the Engineer of Record (EOR) should describe in the Explanatory Notes/Comments section of the Design Criteria Sheet for Climate Change Resilience (Appendix A of these guidelines) whether the project included input from a geomorphologist (in which case, attach the report) and to what extent, and should include the following:

- How climate change effects were qualified or quantified
- How the potential for debris floods and debris flows was accounted for in the climate change assessment
- Protective design measures that were employed
- Maintenance measures that are recommended.

On large-design major-retrofit projects, and for regional highway climate impact studies, a Climate Change Risk Assessment is conducted to inform design, and the completed Design Criteria Sheet must include input from geomorphologists. The input from the geomorphologist should, at a minimum, be based upon desktop studies, field investigations, hazard process characteristics, spatial hazard characteristics, and hydrological and hydraulic modelling, including future climate impacts on debris floods/flows, scour, and bank erosion.

Also, monitoring of weather conditions (temperature, precipitation) and land movement rates could be beneficial if a specific site is being investigated. Once a long-enough time series (for example, one climate normal [30-year] period) has been established, using multivariate analysis, specific weather conditions can be associated with the potential for debris floods and debris flows. One important way to reduce highway user risk is to issue highway warnings or implement closures during particularly adverse weather conditions. Those can be provided only with research that identifies thresholds for debris flow or debris flood initiation and then be implemented in real-time.

For smaller highway projects on steep creeks, the EOR should, at a minimum:

- study the watershed characteristics and hydraulic characteristics, such as channel bed materials and channel dynamics, and define the suite of relevant geomorphic processes (e.g., floods, debris floods, debris flows, scour, and bank erosion);
- where available, review site-specific historical hydrologic data (e.g., stream flow from a gauging stations) and geomorphologic data (e.g., topographic maps, channel evolution, temporal changes in landform);
- review recent local and regional case studies on geomorphic and hydrologic climate impacts;
- use desktop tools to study channel bank erosion potential and bed scour; and
- offer design solutions and maintenance measures to protect the highway infrastructure against geomorphic risks associated with climate change.

Current approaches to account for debris flood potential include:

- using historic hydrologic data;
- studying channel hydraulics;
- using the future projected changes to peak flows, and applying greater than a 200-year design return period;
- examining the potential for landslide or other types of outburst floods; and
- employing 2-D numerical modelling.

In addition, EORs should review recent case studies of infrastructure failures due to geomorphic risks and consider factors such as landslides, floating debris, channel migration, and forest fire, when accounting for debris flood potential. Refer to Section 3.0 and Appendix D of *Professional Practice Guidelines – Legislated Flood Assessments in a Changing Climate in BC* (Engineers and Geoscientists BC 2018) for more information on professional practice considerations and debris floods and debris flow hazard assessments.

Mitigation Measures

Methods for mitigating risk due to debris floods and debris flows include avoiding locating highway infrastructure in high hazard areas and designing:

- infrastructure that can be easily remediated such as fords (could be considered in smaller roads with the appropriate signage);
- upsized bridges and culverts (in streams with high bedload transport, culvert capacity, and gradient, the aim should be to reduce sedimentation in the culverts, or blockage of culverts by debris at the inlet);
- stronger foundations to withstand shear forces and impact forces (many bridges founded in soils, i.e., glacial or fluvial sediments, may require armouring of bridge approaches);
- unconfined deposition areas and sedimentation forebays;
- lateral, deflection, and terminal berms or basins, check dams, or barriers (these are expensive and require detailed understanding of the various effects, such as downcutting of the stream if sediment-starved, creation of knickpoints, or reduction in spawning gravel for fish, and are associated with substantial maintenance costs in cleaning out the debris and repairing damage);
- debris racks/grizzlies;
- flexible barriers in the form of well-anchored nets;
- overflow culverts;
- rip-raps; and
- concrete/log-crib/gabions/masonry check dams.

The key is to quantify the effects of climate change as well as possible, and adjust the expected design magnitude accordingly. The EOR should consider these and other design strategies and use a risk-based approach (e.g., utilizing the PIEVC Protocol) to inform design decisions.

Where recent regional reports documenting climate change impacts to relevant geomorphic processes are available, highway design professionals are expected to consider the information in such reports to inform their design solutions. Strict rule-driven, risk-based approaches could result in unaffordable mitigation. Rather, risk-informed approaches should be chosen that should, ideally, rely on detailed regional prioritization studies that identify those sites with the highest risks to highway users.

Channel Bed Stabilization Mitigation Measure

The association with climate change requires highly specialized study, which must begin with isolation and identification of factors that explain a specific landslide type. In coastal British Columbia, and specifically for debris flows, these factors will always be a combination of antecedent moisture conditions and a measure of rainfall intensity, ideally paired with snowmelt proxies. However, researchers must have a robust inventory of landslides at least to the exact day and time of occurrence and frequency, and a robust array of weather station data over an extended period (at least a decade of data). Otherwise, any statistical analysis will be hampered with severe difficulties. Further, specifically for debris flows, watersheds need to be classified as to their supply limitations (channel supply-limited and unlimited, and watershed supply-limited and unlimited). Only then can a climate change response be predicted with reasonable confidence.

Debris floods exert high shear stresses on stream banks, and can cause substantial erosion as the existing channel widens to accommodate the increased discharge (both water and sediment) during an event. Predicting bank erosion reliably is difficult. Bank erosion can be assessed through a combination of historical air photo interpretation and a hydrologic assessment (or event reconstruction); the amount of erosion observed between air photos can be related to the largest flow that occurred over the period.

This should be the minimum required work, even though this approach has several limitations, namely that:

- observed erosion may result from multiple events between air photos, rather than a single event;
- the number or magnitude of events occurring over the period of air photo record may be too small to characterize a relationship between discharge and erosion magnitude; and
- the historical event magnitudes may not represent the future conditions.

The latter consideration is especially important in the case of climate change, which may increase the water discharge and/or bulking factor for future debris flows and debris floods, as well as the event frequency.

For large or high-consequence projects, a physically-based model, the Stochastic Channel Simulator (STOCHASIM), can be applied to complement air photo analysis. The model was developed based on stream table experiments and numerical modelling conducted at the University of British Columbia (Eaton et al. 2017; Davidson and Eaton 2018), to predict bank erosion for a range of return period floods. STOCHASIM assumes that erosion initiates when the shear stress is high enough that the coarse material on the channel bed is fully mobilized—leading to destabilization of the channel bed and banks—and that widening continues until the shear stress drops below the critical value. As suggested in the name, the model is stochastic; it is run several hundred or thousand times, with parameter values for each run randomly selected from a distribution centered on the user-input value. The model then produces probabilistic estimates of bank erosion for each flood return period (Figure B.8 - 1).

Certain inputs are required to run the model: discharge, channel geometry, gradient, grain size (D84), and channel roughness (Manning's n). Although most inputs can be determined from a desktop assessment (e.g., LIDAR, satellite imagery), a field assessment is typically conducted to measure grain size at multiple locations along the channel. The model should be used in combination with air photo, satellite imagery, or LiDAR analysis, where possible, in order to calibrate the model to the observed erosion during the historical periods with known flows.

STOCHASIM is appropriate for use in coarse-grained channels with relatively cohesionless banks, where channel adjustment occurs primarily through widening rather than through bed scour, and is therefore often appropriate for steep creeks on alluvial fans in British Columbia. In finer-grained meandering rivers, which are characterized by gradual erosion at outer bends and a relatively constant channel width, a different method should be used, such as FLO-2D (2-D mobile bed hydraulic modelling) or MIKE 21C (2-D modelling for simulating bed and bank erosion, scouring, and sedimentation).

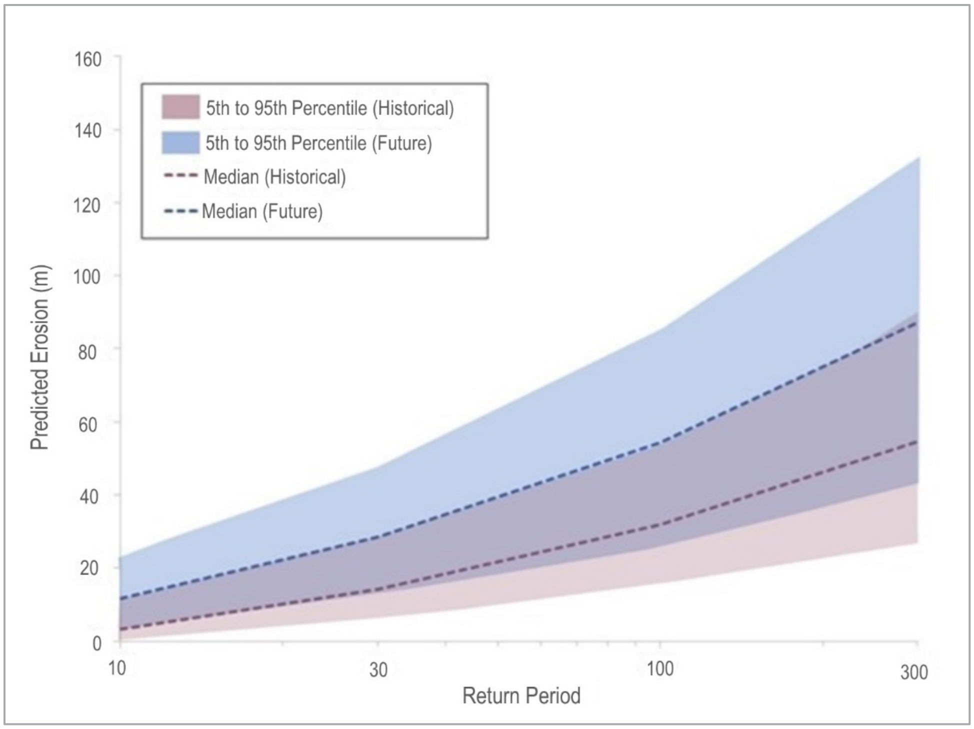


Figure B.8 - 1: Probabilistic Estimates of Bank Erosion for a Steep Creek for Return Periods Ranging from 10 Years to 300 Years.

Predictions based on the historical hydrology are shown in red, and the future conditions (which account for changes in precipitation associated with RCP 8.5) are shown in blue. For a 100-year return period event, the model predicts that there is a 5% probability of erosion exceeding 50 m, whereas under future climate conditions the probability of exceeding 50 m of erosion increases to 50%, and there is a 5% chance that erosion will exceed 80 m.

Case Studies

The following recent case studies of British Columbia Ministry of Transportation and Infrastructure (BCMoTI) infrastructure showcase how debris floods and flows have impacted the provincial highway infrastructure. Questions that need to be considered from these case studies include the following:

- Would these events have occurred without climate change? If yes, would they have occurred at the same frequency and/or magnitude?
- What is the likely change in the future for those specific case studies?
- Will there be more of those events, or fewer? If there will be more, will they be larger, the same size as without climate change, or smaller?
- Could there be an entire process change under a climate change scenario; for example, a single-thread river turning into a braided stream as it can no longer cope with the abundance of sediment introduced by hillslope processes?

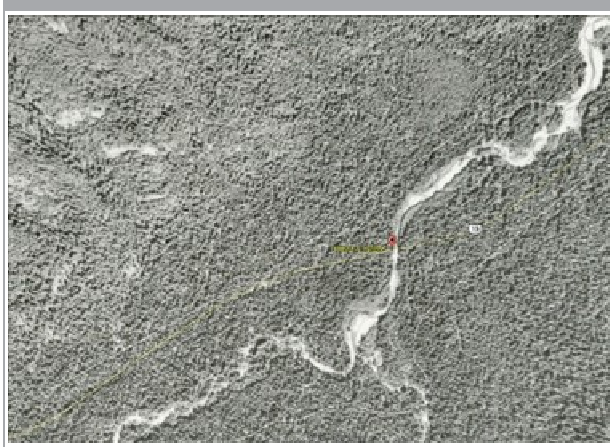
Case Study 1: Eve River Bridge

The Eve River Bridge is a three-span structure, located on Highway 19, with spread footing foundations at the abutments and piers. Eve River has a predominately pluvial flood regime with peak flows typically occurring during the winter months. Logging has occurred in the watershed since the 1970s. The upstream channel has a large amplitude left-hand-turn (looking downstream) meander bend.

Historic air photographs show the channel transitioning from a single-thread straight alignment in the 1960s, to meandering downstream of the bridge crossing and braided downstream of Highway 19 (Figure B.8 - 2 below). Field observations by the highway maintenance crews suggest the upstream meander bend began to form in early 2000s. Ongoing meander bend migration increased the skew angle of the channel alignment relative to the bridge waterway opening, reduced the hydraulic and sediment transport capacity, and increased the risk of undermining the spread footing foundations of the bridge. To mitigate the bank erosion activity, the upstream channel was armoured with riprap spurs and revetment.

Figure B.8 - 2: Photographs of the Eve River Bridge Location: 1967 to 2017

AIR PHOTOS OF THE EVE RIVER



1967 (Before Highway 19 Construction)

1996

2002

2016

UPSTREAM CHANNEL, LOOKING UPSTREAM FROM THE EVE RIVER BRIDGE

2005

2008

2010

2014

DURING RIVER TRAINING CONSTRUCTION

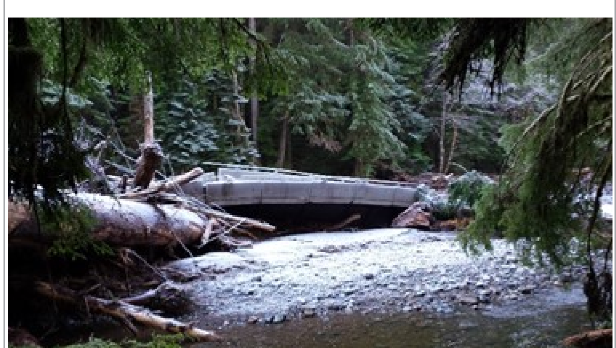
2017

Case Study 2: San Josef River Bridge Crossing

The San Josef River Bridge crosses the San Josef River in northern Vancouver Island. The watershed has peak flows typically generated by large rainfall events in fall and winter. In early November 2014, a major storm system moved across the region, resulting in 189 mm of rainfall during a 24-hour period at a nearby weather station. Also, a downstream hydrometric station recorded peak flow with return period in the order of 200 years. The storm event triggered numerous landslides and resulted in high peak flows within the watershed, which generated a debris flood at the bridge crossing.

As a result, the San Josef River Bridge suffered catastrophic failure. The bridge superstructure was carried downstream by 150 m, the riprap bank protection was damaged, and abutment walls were undermined. The design criteria for the replacement structure incorporated consideration for debris flow, which included freeboard allowance for debris passage underneath the bridge low chord, impact loading from large floating woody debris, and hydraulic drag and buoyancy load from accumulating debris.

Figure B.8 - 3: Photographs of the San Josef River Bridge Location - 2011

PHOTOGRAPHS OF THE SAN JOSEF RIVER BRIDGE LOCATION	
	
2011 (before the event of November 2014)	*2011 (upstream channel)*
	
Landslides in the upper watershed	*Debris accumulated in the channel*
	
Channel immediately upstream of the bridge	*Superstructure of San Josef River Bridge*

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Eaton BC, MacKenzie L, Jakob M, Weatherly H. 2017. Assessing Erosion Hazards Due to Floods on Fans: Physical Modelling and Application to Engineering Challenges. Journal of Hydraulic Engineering. 143(8). doi: (ASCE)HY.1943-7900.0001318.

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APPENDIX C: CLIMATE CHANGE TOOLS AND RESOURCES FOR ADAPTATION

For an up-to-date overview of climate change and list of tools and resources for climate change adaptation, visit the Engineers and Geoscientists BC Climate Change Information Portal:

- egbc.ca/Practice-Resources/Climate/Climate-Change-Information-Portal

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