STANDARDS RESEARCH

Peak Flow Assessment under a Changing Climate: Recommendations for the Canadian Highway Bridge Design Code

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Foreword

Hydrologic and hydraulic analysis for bridge design is dependent on flow estimates at site-specific watershed, river, and reach locations. Changes in peak flow magnitude under climate change are unknown or poorly understood due to the complexity of watershed hydrologic responses and their climatic drivers. The resulting lack of consistency in the climate-informed flood frequency analyses that practitioners currently apply to Canadian bridge and highway design may contribute to uncertainty and risk. This research report evolved from the recognized need for standardized and simplified tools to support hydrological practitioners in Canada in completing climate change-informed peak flow assessments. Current practice for small rainfall-dominated watersheds recommends use of temperature scaling approaches applied to rainfall intensity using the Clausius–Clapeyron relationship. Because this approach is well documented, small rainfall-dominated watersheds are not included in this report. The recommendations presented in this report are intended to support future editions of CSA S6, *Canadian highway bridge design code* [1], and to help advance a common method/approach in executing hydrological investigations and flood frequency analyses for bridge design in Canada. However, these recommendations can also be applied to similar investigations where peak flow investigations in a changing climate are needed, such as flood hazard assessments.

The findings presented in this report draw from personal experience of the authors, an extensive literature review of peak flow estimation under climate change, and interviews with key practitioners and researchers from across Canada. While the literature review focuses on tools and processes used for regionalization and flood frequency analysis from both the academic (peer-reviewed) literature and practitioner reports, the interviews are meant to highlight lessons learned from the implementation of peak flow estimation by experts. Together, these guide the creation of a framework to advance this knowledge into a set of procedures and tools that can be used by practitioners in estimating peak flows for bridge sites across Canada. It should be noted that while this study establishes the framework and recommendations for these procedures and tools, it does not include the development of such tools. This aspirational undertaking would be the objective of a subsequent implementation program.

Table of Contents

Glossary

AR – Assessment report, which is the documentation accompanying a release of the CMIP experiments. (Refers to IPCC's AR.)

CMIP – Coupled Model Intercomparison Project experiments, which are a group of global climate models (GCMs) from different climate modelling institutes around the world that all run a series of carbon emission scenarios to represent different trajectories of climate change across a set time horizon.

ESM – Earth System Model, or simulation of all processes on Earth, including biological, chemical, biogeochemical, as well as climate and hydrology. They are used as improved representations of surface processes within GCMs.

FFA – Flood frequency analysis, or the assignment of a probability of occurrence to a specific streamflow threshold.

GCM – Global climate model or general circulation model, which refers to the global scale simulation of climate variables used for climate change assessment.

GMT – Global mean temperature rise, which represents the increase in global average temperature above "pre-industrial" levels (typically reported relative to temperature in 1880).

IDF – Intensity-duration-frequency, which is an approach applied for assessing rainfall-runoff resulting from rainstorms by correlating the amount of precipitation (intensity) to the length of rainfall (duration) to arrive at the severity of the storm (frequency or return period).

IPCC – Intergovernmental Panel on Climate Change, which is the international regulatory body controlling the release of the CMIP experiments.

LEs – Large climate ensembles, which represent ensembles derived from multiple GCMs and emissions pathways.

POT – Peaks over threshold, which is a statistical method for FFA that uses observations that are above a given threshold, called exceedances. POT are defined to identify types of events, such as snowmelt from rainfall derived peak flows.

Practitioner – An individual who possesses the knowledge, skills, training, experience, and other requirements to perform an FFA. Used interchangeably with qualified person.

Qualified person – An individual who possesses the knowledge, skills, training, experience, and other requirements to perform an FFA. Used interchangeably with practitioner.

RCM – Regional climate model, which refers to the dynamically (using a model) downscaled representation of global climate processes and variables for a specific region of interest.

RCPs – Representative concentration pathways, which are from the coupled model intercomparison project fifth assessment (CMIP5). Also see SSPs definition, which applies to CMIP6.

RFA – Regional flood frequency analysis, which is used to estimate the magnitude of flood events of various return periods across homogeneous regions, as opposed to at single sites or gauges.

SMILEs – Single model initial-condition large ensembles, which represent an ensemble derived from a single GCM but with perturbed initial conditions and boundary conditions for each member.

SSPs – Shared socioeconomic pathways, which are from the coupled model intercomparison project sixth assessment (CMIP6) representing different greenhouse gas or emissions scenarios and application of a range of offset technological innovations to mitigate climate change in the future. Also see RCP definition, which applies to CMIP5.

Executive Summary

A leading cause of bridge failures is due to scour and erosion around bridge piers and abutments. Suitable protection against these hazards, as well as determining the required hydraulic opening size of bridges that span watercourses is largely dictated by the estimated peak design flowrate. This flowrate allows practitioners to manage flow velocities and acceleration through the bridge site, to ensure adequate bridge soffit clearance is provided, and to assess in-stream and overbank flows. By providing an adequate bridge span and hydraulic opening, scour, erosion, and over-topping can be managed. In the past, design flow estimates were heavily dependent on historical records and typically relied on completing frequency analysis of historical observed streamflow data or a proxy thereof. These historical streamflow-based estimates are becoming increasingly less valid under a changing climate, particularly for bridge infrastructure that is intended to last for decades. For non-rainfall-dominated watersheds (i.e., watersheds in which peak bridge-related flooding cannot be linked directly to individual rain events), hydrological modelling of the contributing watershed is required to estimate future condition peak flow. This approach can overcome the assumption of climate stationarity, which is a key assumption of traditional hydrologic assessments. However, hydrologic modelling of watersheds can be a significant undertaking and the level of effort to build and analyze a climate-driven watershed hydrological model may not be commensurate with the risk imposed at the subject bridge site.

The research conducted for this report investigated the range of simplified and standardized approaches that would allow practitioners to estimate future condition peak flow at bridge sites across Canada. This report is the first step toward an initiative with the aspirational goal of developing upper bound factors that can be applied to frequency analysis of historical records to reflect the impacts of climate change. Although the underlying flood-generating mechanisms may be changing, developing “bounding curves” and resulting “delta-change factors” can be justified by comparing peak flows from modelled historical and future climate windows. The delta-change factors could then be applied to estimate conservative future condition peak flows at other locations within the same hydrological region. Thus, a practitioner could use traditional peak flow estimating procedures, such as single station frequency analysis or regional approaches, and apply a delta-change factor that represents the maximum change in peak flow expected to occur based on a specific emission scenario and time horizon (collectively referenced as degrees of global warming). Delta-change factors would provide the basis for resilient design (i.e., low probability of exceedance) in the absence of detailed, site-specific hydrological assessments driven by future climatic parameters. In turn, this would provide a level of consistency for completing peak flow assessments for bridge design in a changing climate, which would benefit owners and practitioners alike by reducing engineering costs while still incorporating hydrological expertise into the assessments.

While the ultimate objective is to develop a geographical dataset that allows practitioners to apply a delta-change factor to historical flood frequency analysis of naturalized open water conditions to account for climate change, this report is limited to investigating the feasibility of such an endeavour and providing recommendations for an approach and the expected limitations. The investigation included a review of relevant studies and considered whether they could be leveraged or emulated at a national scale. Due to the rapid evolution of hydrologic studies that span a variety of spatial scales, landscapes, and hydrologic conditions, this report identified the most current, robust, and relevant approaches, and included interviews with a variety of agencies and key individuals responsible for peak flow estimation.

This report concludes that a national dataset of bounding curves can be derived from a Canada-wide modelling effort that performs a climate change impact assessment for peak flow estimation. From these bounding curves, delta-change factors can be developed for various hydrologic regions or basins across Canada and used to scale up historical, at-site practitioner-derived peak flow estimates for bridge design to account for climate change impacts. The recommended approach achieves a balance between an adequate amount of rigour for climate adaptation measures, as recommended by the Intergovernmental Panel on Climate Change (IPCC) sixth assessment report (AR6), while recognizing the practical limits of practitioner resources, time, and budget constraints.

"A leading cause of bridge failures is caused by scour and erosion around bridge piers and abutments."

1 Introduction

1.1 Understanding the Problem

A leading cause of bridge failures is caused by scour and erosion around bridge piers and abutments [1]. Suitable protection against these hazards, as well as determining the required hydraulic opening size of bridges that span watercourses is largely dictated by the estimated peak design flows that impact velocities and hydraulic grade lines. In the past, the design flowrate was typically estimated based on a frequency analysis of historical streamflow data or a proxy thereof. These historical streamflow-based estimates are becoming increasingly less valid under a changing climate. In Canada, climate change has affected the frequency, magnitude, and timing of natural disasters involving water and flooding [1], necessitating a closer examination of changing peak flow frequencies and magnitudes resulting from non-stationary anthropogenic and natural causes.

The Canadian Engineering Qualifications Board released a national guideline pertaining to principles of climate adaptation and mitigation that provides specific guidance for the engineering profession, and clearly establishes the need to integrate climate change into engineering practice and design [2].

The current CSA S6, Canadian highway bridge design code (CHBDC) [1] and related commentary [3] provide limited guidance for estimating peak flows, stating that "a hydrologic assessment shall be completed" using methods as "required by the owner." This vague wording may lead to variation in the design of bridges that are meant to be in place for 75 to 100 years and will be subjected to floods of changing magnitude. More rigorous standards, similar to those in place for Canadian dam design [4], are needed.

Under a future climate, the temporal and spatial changes to rainfall, snowmelt, and rain-on-snow characteristics could lead to changes in the flood-generating mechanisms responsible for peak flows at a bridge site, causing significant shifts in the frequency, severity, and timing of runoff. For small watersheds, where the dominant flood mechanism is the result of runoff generated from rainfall, intensity-duration-frequency (IDF) curves in combination with event-based rainfall-runoff methods are generally used to assess peak flow. The current recommended temperature scaling approach, described in CSA Plus 4013, *Technical guide: Development, interpretation and use of rainfall IDF information: Guideline for Canadian water resources practitioners* [5], can be used to estimate future peak flows. However, for larger and more complex watersheds, where peak flows are governed by unique and varying hydrological conditions, watershed modelling upstream of the bridge site is typically required to estimate future peak flows. Additional guidance and support is needed for the engineers and geoscientists who are tasked with estimating these peak flows as a part of bridge design in a changing climate.

1.2 Rationale for Considering Peak Flow Estimation in the Code

An updated version of the CHBDC and related commentary (CSA S6.1) is in development, as described in the CSA Group research report, "Climate Change Provisions for CSA S6:25 Canadian Highway Bridge Design Code: Findings and Recommendations" [6]. The update will provide clearer direction on the common method/approach, including specific actions required for hydrologic analysis and peak flow estimation at bridge sites. This could be achieved through an improved understanding of current (i.e., historical) and future hydrological conditions, with the goal of improving the resiliency of bridge structures in Canada.

Climate change-informed hydrological assessments represent a significant step in the level of expertise, resources, and effort required to estimate peak flow at bridge sites. Many organizations and practitioners may not have the expertise or the capacity to undertake in-depth, robust climate-adjusted hydrologic modelling and appropriate interpretation and reporting for a bridge project. Furthermore, the level of effort required to build and analyze a climate-driven hydrological model may not be commensurate with the risk imposed on the subject bridge or the often limited budget and schedule available to complete the analysis.

Recognizing these challenges, some Canadian jurisdictions apply an upper bound factor to frequency analysis of historical records to address the impacts of climate change. Although this approach may lack a direct scientific basis (because the underlying flood mechanisms may be changing), there may be scientific justification for developing "bounding curves" and "delta-change factors" from a database that compares peak flows from modelled historical and future climate normal periods. The resulting upper bound delta-change factors could potentially be applied to estimate climate-adjusted peak flows at other locations within the same hydrological region. This approach could provide a more readily available Canada-wide spatial database of adjustment factors that could be applied to historical flood frequency analyses, thus benefiting bridge owners and practitioners alike.

The ultimate goal of this "initiative" is to develop a set of delta-change factors specific to all regions across Canada that could be used by practitioners to predict peak flow values that account for climate change. The practitioner would apply these factors to the peak flow estimates derived from traditional hydrological methods that assume a stationary climate. To develop the delta-change factors, calibrated watershed hydrological models would need to be forced by downscaled climate data, such that the changes in peak flow estimates could be made by comparing current and future condition results. The intent is to develop bounding curves that could be used to derive conservative upper bounds to expected changes in peak flow based on selected representative concentration pathways or shared socioeconomic pathways (RCPs or SSPs) scenarios and time horizons (collectively referenced as degrees of global mean temperature rise, °GMT, relative to the 1987–2016 baseline time period).

The bounding curves and associated conservative delta-change factors would provide the basis for resilient design (i.e., low probability of exceedance) in the absence of detailed site-specific hydrological assessments driven by future climatic parameters. Thus, a practitioner could use traditional peak flow estimating procedures, such as single station frequency analysis or regional approaches, and apply a delta-change factor to address the impacts of climate change. The values developed would be conservative from a bridge design perspective and would provide more extreme peak flow estimates than those that might be derived from undertaking a full site-specific hydrologic analysis. Under no circumstances should the adjustment factors decrease peak design flows from present day estimates, even if future projections indicate decreasing peak flow. This recognizes that a bridge structure must be designed to address current conditions, as well as conditions that may be encountered throughout its life span.

Recognizing the significant effort required to develop a national dataset of bounding curves and delta-change factors, **the goal of this report is to investigate potential approaches and provide recommendations to inform the development of such a dataset under a future project.** The development of a national dataset of bounding curves and delta-change factors ("the initiative") is beyond the scope of this report.

2 Investigating Peak Flow Estimation across Canada

To understand the current state of practice and knowledge relating to peak flow estimation across Canada, along with how climate change impacts are considered (if at all), the research included a review of the current literature, a review of research and development investments, and a survey of practitioners and agencies involved with climate-informed peak flow estimation across the country. The key findings are discussed in Section 2 of this report, while recommendations related to the initiative are presented and discussed in Section 3.

2.1 Current State of Knowledge: Review of Existing Studies

The literature demonstrated that approximately one half to one third of Canada's areal extent has been modelled in various studies [7], [8], from which it may be possible to derive peak flow estimates for watersheds under climate change at various extreme quantiles ranging from a return period (RP) [1] of 100 years (annual exceedance probability, AEP = 0.01) to 10,000 years (AEP = 0.0001). Several studies use the Canadian model parameter experiment (CANOPEX) catchments (686 basins) [9] and large climate ensembles (LEs) to do large-scale climate change analyses. The limitation is that each study uses its own set of models, climate ensemble, emissions scenarios, bias correction techniques and datasets, and modelling methods that are not directly comparable from one basin to the next. Therefore, this report extracts methodological lessons from these studies to compile best practices and lessons learned, as presented in this section.

2.1.1 State of Climate Change Understanding across Canada

Since 2014, the Canadian government has invested in several reports, frameworks, and analyses to summarize the impacts of climate change on the Canadian landmass and biota. For example, Canada's Changing Climate Report conducted and summarized an extensive review of climate change across Canada [8], noting high confidence and certainty in continued warming and increasing precipitation, though with varied amounts and certainty across Canada. Hydrologically, there is high confidence of more frequent and extreme water shortages in summer months and increasing winter flows with earlier spring peaks. the report states that "the rate and magnitude of climate change under high versus low emission scenarios project two very different futures for Canada," noting the "profound effects" under the high carbon emissions scenarios and the lower likelihood of achieving lower emissions scenarios, which would require Canada and the rest of the world to attain near-zero carbon emissions early in the second half of the 21st century [10]. Since 2019, global society has continued to follow the medium-to-high emissions trajectories, with mean global warming expected to exceed 2.0oC in the 21st century compared to pre-industrial levels [10].

Data underpinning Canada's Changing Climate Report was made available in a web-based interface (ClimateData.ca) and in the Canadian Climate Data and Scenarios database [11], with support for practitioner adaptation and mitigation planning provided through the Canadian Centre for Climate Services branch. Similar international data repositories for global analysis and in support of the IPCC assessments are provided by the Copernicus Climate Change Service [12].

From the data and reports, it is now generally accepted with high agreement that Canada's climate has warmed since 1948 and will continue to warm throughout the 21st century [8]. There is also general agreement that precipitation will increase across most regions of Canada, though the models disagree on the amount and timing of these increases [8], [13]. This will result in increasing runoff for many rivers in Canada, with a shift toward earlier snowmelt peaks (warmer springs) and an increase in the number and frequency of rainfall-driven peak flow events [14], [15]. However,

1 Return period (RP) and annual exceedance probability (AEP) are interchangeable, with [RP = 1/AEP]. The latter term is preferred to highlight ongoing risk each year and is often expressed as a percentage.

across the Prairies, many models project decreasing runoff during summer and early fall due to increasing evapotranspiration losses in inflow-limited Prairie basins [16]. Furthermore, many Canadian watersheds may experience reduced peak flows going forward due to reduced snowpack with peak freshet events trending lower and earlier in the season. This would be a result of more precipitation falling as rain rather than snow over the historical snow accumulation period. It will therefore be important for practitioners to determine whether the highest peak flows are experienced during current or future time periods extending over the design life of a bridge structure.

2.1.2 Assessing Climate Change in Canada

Several significant Canada-wide initiatives have been undertaken to document and understand the current state of Canada's climate and the anticipated changes [8], as well as advances in data dissemination and availability [12], [17], [18]. The IPCC is the international authority responsible for summarizing climate change assessments and follows the World Climate Research Program (WCRP) releases of the Coupled Model Intercomparison Projects (CMIP) experiments, which provide different generations of multi-model ensembles that are used around the world to assess climate change. At the time of writing, the CMIP6 was the most current iteration [19].

There is a high degree of uncertainty about the future climate due to different global climate models (GCMs), internal variability, and emission scenarios (i.e., SSPs or RCPs). Each climate model possesses a degree of uncertainty that stems from its structure (i.e., algorithm, numerical solution, grid structure, parameterization) and consequent response to external radiative forcing. To address structural uncertainty, the CMIPs include a large selection of GCMs from different climate institutes that contribute to the experiments. Uncertainty related to internal climate variability is generally addressed by increasing the ensemble size through multiple realizations of initial model conditions. To address uncertainty related to future emissions, each model is run under a variety of SSPs (or RCPs) that represent a range of greenhouse gas concentration forcings of the atmosphere that, globally, result in different trajectories of climate change impacts, including precipitation, temperature, and other variables (e.g., streamflow).

Processing climate data for use in impact model simulations introduces added uncertainty. The coarser resolution of GCMs (i.e., global scale) means they may not adequately represent the region of interest. Therefore, it is often beneficial to refine their resolution through downscaling to improve the link between atmospheric changes and land surface processes. This procedure results in regional climate model (RCM) output, if the downscaling uses a physically based model to achieve the higher resolution, instead of a statistical method of downscaling [15]. Regardless of the downscaling method, bias correction is necessary to improve the GCMs' representation of local-scale climate processes and inter-relationships between different variables (e.g., temperature and precipitation) [20]. Depending on the method of downscaling and bias adjustment procedures selected, there will be slight to significant differences in the outputs [21] and this added uncertainty would be carried forward if it is subsequently used for hydrological studies and peak flow assessment.

If the intended output of the climate assessment process is a hydrologic variable (e.g., peak flow), then climate model simulation data are typically fed into a watershed hydrologic model. This establishes a modelling chain, with every step in the modelling chain introducing its own internal and structural uncertainty to the overall or total uncertainty [22], [23], [24]. Added to this is the parameterization, or the process of establishing the "constants" of internal, physics- or concept-based equations within each step in the modelling chain [25], [26].

This raises the question of reliability and confidence in climate impact assessment modelling studies. How can there be confidence in future projections with this much uncertainty? The IPCC AR5 guidance note provides direction on consistent treatment of the uncertainty among climate model projections and suggests a qualitative to quantitative (probabilistic) matrix based on level of agreement among the various models [27]. Another guide for practitioners is provided in Environment and Climate Change Canada's

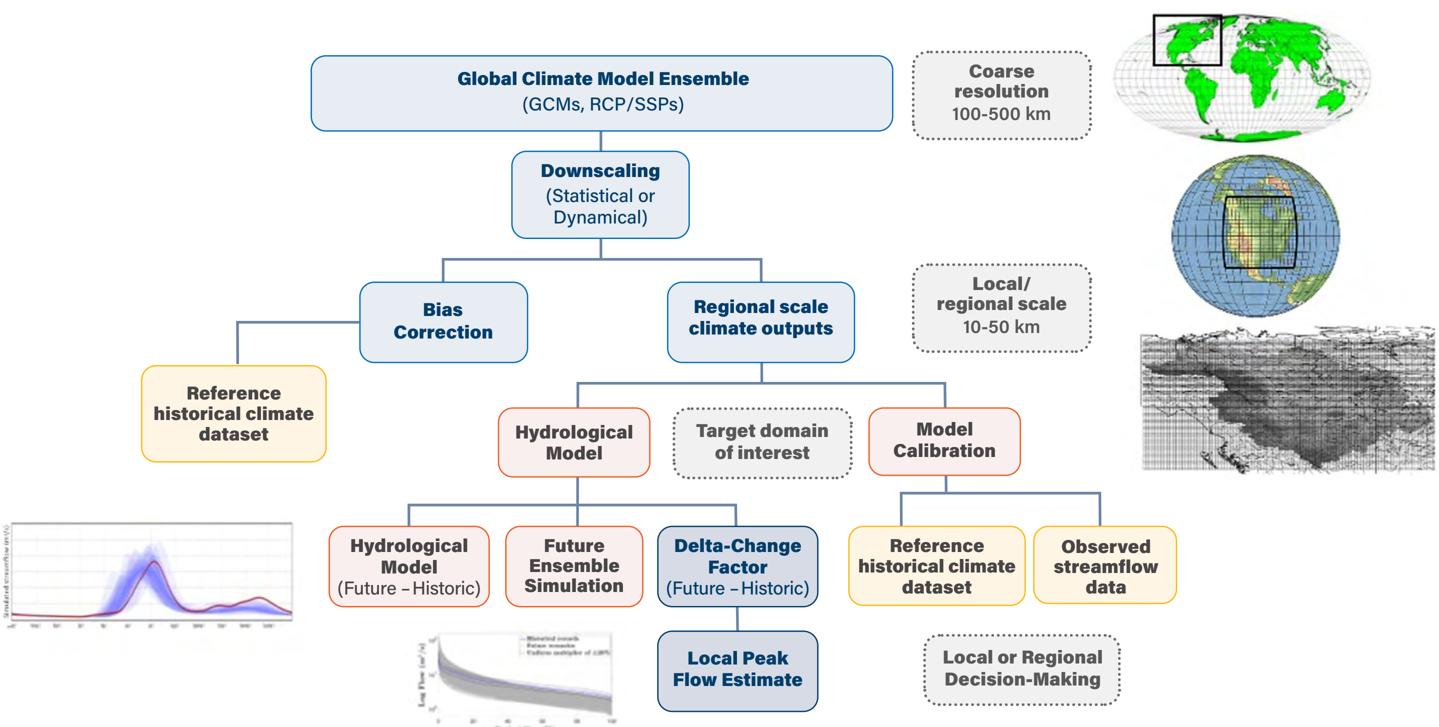
(ECCC) Climate-Resilient Buildings and Core Public Infrastructure report, which assigns confidence tiers (1, 2, or 3) that are defined as the "level of 'trust' that can be placed in quantitative factor assessments for particular climatic design variables" [28], [29]. In addition, the IPCC's Climate Change 2021: The Physical Science Basis provides guidance for mapping projected change and disentangling "signal-to-noise" from climate models [30]. These documents, along with the recommendations presented in Section 3 of this report, provide useful guidance to inform decision-making for assessing design flow under climate change.

2.1.3 Best Practice for Climate Change Impact Assessment

This review of best practices related to climate change impact assessment was conducted to determine the potential impact of climate change on the hydrological response of watersheds in various regions across Canada, and the potential impact on peak flow. The net impact climate change has on peak flow is of particular interest, while the timing and volume of streamflow is of general interest. Current best practices agree on several key components of climate change impact assessments, as described in a report from the National Research Council (NRC), which also provided an initial roadmap for climate change impact studies related to floodplain mapping needs that include hydrologic and hydraulic components [31].

The basic components of hydrological assessments under climate change are represented by the different colour boxes in Figure 1. Blue indicates steps in selecting and preparing the climate model ensemble from GCMs, while red represents hydrological modelling components, and dark blue represents output from the analysis (i.e., local peak flow impact assessment). Finally, yellow represents the application or need for reference (i.e., historical) datasets. Best practices within the literature for each of the following components are outlined in sections 2.1.3.1 through 2.1.3.5.

Figure 1: Key components of a climate change impact assessment (adapted from [31]).



2.1.3.1 Selection of Climate Model Ensemble

Climate models are numerical representations of the physical world and atmosphere. They are complex and designed to represent long-term changes to the climate, including the range of climate variability under uncertainty. Climate model simulations are calibrated (i.e., bias corrected) to represent the statistical parameters of the distribution of historical climate, and not the recorded time series of climatology (i.e., sequence of events) [30]. In this way, they cannot be directly compared to historical observations, rather they are compared to the statistical distribution properties of historical observations (i.e., moments of the distribution: mean, variance, skew, and kurtosis). When selecting a climate model ensemble, the following important factors that help frame the various components that contribute to uncertainty must be considered [30]:

- Model structural uncertainty;
- Climate scenario uncertainty; and
- Natural and/or internal variability.

Climate model selection for impact studies should use a subset of data from the most recent CMIP ensemble to leverage the most current advances in climate and Earth system models, which provide increased resolution and accuracy to represent atmospheric and surface processes. The selection of climate models should consider the geographical scope of the project and screen out any models that are known to produce unrealistic transient climate response to greenhouse gas (GHG) concentrations (known as "hot models") [32].

The uncertainty in climate modelling results from differences in the numerical equations, parameters controlling these equations, and the initial and boundary conditions specified among and within the different GCMs. Different RCPs or SSPs represent society's ability to buffer the climate crisis by reducing GHG emissions or by mitigating their harmful effects through technological innovation. Because there is no single best model (GCM), and the future trajectory of emissions is unknown, a selection of emission pathways is typically applied to multiple GCMs to represent different climate forcings and the range of possible outcomes. Although computationally intensive across large domains, this approach captures a wider range of uncertainty or spread of the future projections [28]. Alternatively, rather than specifying the emission scenarios, current practice in climate modelling promotes specifying a threshold of warming (i.e., °C GMT rise) independent of when this is expected to occur. This approach allows a more direct comparison of current versus future outcomes with the emission scenario being implicitly represented.

For a specific region in Canada, if there is information correlating the time horizon with which a corresponding change in temperature is anticipated under specific SSPs or RCPs, then it may not be necessary to include multiple emissions pathways in a study. In this case, specific emission scenarios and corresponding temperature thresholds that align with the 75-year design life of a bridge could form the basis of analysis. For example, as shown in Table 1, using CMIP5 RCP 6.0 data relative to the pre-industrial baseline would result in approximately 2°C GMT rise over the 75-year design life of a bridge structure.

Internal variability can be represented and framed by including sufficiently large initializations of the same GCM. The use of single model initial-condition large ensembles (SMILEs) allows flood frequency analysis to be conducted on a large dataset resulting from multiple realizations [33] from the same model. However, because a SMILE is developed by varying initial and boundary conditions of a single GCM, it results in a narrower range of climate and hydrological responses compared to an LE consisting of multiple GCMs and emissions pathways. Selecting a SMILE as part of an impact assessment workflow must confirm that the use of a single GCM and emission pathway is suitable for the stated objective [33]. Ultimately, an LE comprised of multiple GCMs and initial and boundary conditions would capture a larger range of possible outcomes, including the extremes that would influence peak flow estimates [34]. In a 2015 study, Cannon *et al.* [35] outlined various considerations for ensemble selection.

Table 1: Change in Global Mean Temperature relative to the 1987-2016 baseline period (data based on CMIP5 and derived from KNMI Climate Explorer [27]. Table reproduction is a copy of the version available at [https://climate-scenarios.canada.ca/?page=buildings-report].

ΔT	RCP 8.5	RCP 6.0	RCP 4.5	RCP 2.6
+0.5°C	2023			
+1.0°C	2035	2046		—
+1.5°C	2047	2070		—
+2.0°C	2059	2087	—	—
+2.5°C	2069	—	—	—
+3.0°C	2080	—	—	—
+3.5°C	2090	—	—	—

2.1.3.2 Selection of Downscaling and Bias Correction Methods

Downscaling and bias adjustment of GCMs is typically needed in hydrological studies due to the mismatch of coarse GCM (i.e., global scale) resolution to the finer scale of hydrological interactions. Deriving site-specific peak flow estimates demands higher resolution of the hydrological model both in time and space. Often, an RCM is used to dynamically (i.e., numerically model) downscale the GCM [36], but statistical methods can also be used [37]. While the choice of approach will impact the overall results, the uncertainty of the downscaling and bias adjustment is typically encompassed within the larger uncertainty envelope generated by the GCM ensemble [38]. Consistency in methodology is essential to ensure adequate consideration of robust bias adjustment techniques, computational limitations, as well as consistency in the data used for the bias adjustment itself (i.e., it should be consistent with the data used to calibrate the hydrological model). The direct link between temperature and precipitation changes resulting from the Clausius–Clapeyron relationship, and if possible, multivariate correction (i.e., simultaneous and consistent correction of temperature and precipitation from the GCM) should also be performed to preserve the correlation between variables [39], [40].

While dynamical downscaling may be the most physically accurate, it is generally not feasible across large domains (i.e., all of Canada) without significant computational investment. To reduce computational demand, some studies consider only a single GCM or single SSP or RCP (i.e., SMILEs). For example, the ClimEx ensemble [41] is a 50-member ensemble of the Canadian RCM, version 5 (CRCM5) at a 10 km x 10 km grid over northeastern North America that used the Canadian Earth System Model (CanESM2) as the driving GCM. Intercomparison of different dynamically downscaled RCMs or LEs is possible to improve the understanding of the impact of downscaling from global to regional domains. However, due to the significant computational demand, statistical downscaling is used more often for CMIP ensembles over large domains. In Canada, there are several repositories of statistically downscaled CMIP6 scenarios available Canada-wide [17], [42], [43], as well as new initiatives in development (see Section 2.2.3).

Many bias adjustment techniques exist and are applied in hydrological impact assessment studies [44]. The most common method is quantile mapping to annual or seasonal variations for the variables of interest [13], [35], [45]. It is important to apply multivariate bias correction techniques that consider non-independent changes among temperature and precipitation, such as Cannon's multivariate quantile mapping bias correction [45] or Rajulapati and Papalexiou's precipitation bias correction [40]. The most important issue for the hydrological modelling chain is preservation of the temperature and precipitation correlation structure. However, if a hydrological model requires additional input variables (e.g., wind and solar radiation), then all of these variables should be included in the bias correction. ERA5 is a good source of observation data that includes variables consistent with climate models, but it may not be the best choice for hydrological model calibration [46], which must consider the resolution of the reference dataset. The reference climate dataset used for bias adjustment should be commensurate (i.e., the same or same statistical structure) with that used for calibration of the hydrological model to ensure consistency. ERA5 data have been shown to be commensurate with several reanalyses datasets used across Canada [47], [48], [49]. In the context of the initiative, the Canadian-based

"Because dominant runoff generation mechanisms vary regionally across Canada, the choice of hydrological model will significantly impact the performance and ability to represent hydrological response in specific regions of Canada."

Regional Deterministic Precipitation Analysis (RDPA) data, based on the Canadian Precipitation Analysis System (CaPA) developed by ECCC, may be a suitable dataset [50].

Although bias adjustment methods may have a smaller impact on multi-model climate impact studies than other uncertainties [38], they likely have a greater impact when evaluating extreme events. This is particularly true of watersheds with changing climatic or hydrologic extremes and flow generation processes [51], [52], [53].

2.1.3.3 Hydrologic Model Selection, Setup, and Calibration

Hydrological model selection is a critical choice that will impact the outcome of the peak flow assessment [51], [54]. Because dominant runoff generation mechanisms vary regionally across Canada [55], the choice of hydrological model will significantly impact the performance and ability to represent hydrological response in specific regions of Canada. As such, it is unlikely that one particular model will be the right choice for all of Canada. A key factor in model selection is to ensure that the model structure represents the range of hydrological processes and all dominant runoff generation mechanisms. Model setup and calibration should ensure that all dominant runoff generation processes encountered across Canada (e.g., temperature, precipitation, snow accumulation and melt, glaciers, etc.) are included.

Though significantly more computationally intensive, some of the reviewed studies include multiple hydrological models [22], [56], [57], similar to the IPCC recommendations for climate projections (i.e., ensemble of models). However, generally, current practice is to select the best performing hydrological model, calibrated and validated over the historical period [58]. It is important to establish simulation or performance benchmarks to evaluate acceptable model behaviour [59], [60]. The resolution of the reference climate dataset should be aligned with the basic computational unit of the hydrological model (i.e., model resolution), although the structure of the basic computational unit (e.g., sub-basin or grid) is not as important.

A range of hydrological models have demonstrated success in hydrological assessments for various regions across Canada, including SWAT, MESH, VIC, HYDROTEL, CRM, SAC, WATFLOOD, HYPE, machine learning methods (long short-term memory, LSTM), and many others [22], [57], [61] - [70]. The Raven framework has also been adopted in several studies due to its flexible model structure and ability to perform model structural uncertainty assessments [71].

Previously developed sub-basin delineations that have hydrologically conditioned drainage networks are available through agencies like the United States Geological Survey (USGS) in the form of HydroSHEDS [72] and MERIT Hydro [73] products. Other hydrologic data needed to define the study domain include a digital elevation model, land cover data, soil classification data, and hydrography (i.e., geofabric layers). Several global land cover and soils databases and products exist that are derived from remotely sensed data and are commonly used in the hydrological context, such as those produced by the European Space Agency [74] and NASA [75]. It is important to consider the spatial scale (i.e., resolution) of the basic computational unit for the hydrological model when selecting the geofabric.

The hydrological routing method that the model uses to translate runoff into streamflow is another key consideration. Routing methods are particularly important for studies examining peak flow because the routed streamflow will generate the extreme flow events (e.g., Q95, or upper quantile, timing, and magnitude) [76]. Regulated flow caused by reservoirs, dams, spillways, and diversions that alter the flow path or routing of flows will also significantly impact the peak flow response. It is therefore important to limit model calibration to natural or minimally altered watersheds due to the errors that can result from non-stationary flow interventions in managed systems. Inclusion of regulated systems could unintentionally be absorbed by model parameters during calibration if these structures or alterations to flow routing are not mathematically represented within the model itself [77].

To calibrate hydrologic models for regulated systems, the reference data would have to be naturalized (i.e., effect of water management removed) or the water management facilities and their historical operating regimes would need to be included within each modelled watershed. Furthermore, to simulate regulated historical and future periods for deriving bounding curves and delta-change factors, potential realizations of historical and future water management facility operating regimes would also need to be envisioned and modelled. This may be considered impractical in the context of the current initiative but could be a valuable undertaking in the future.

In some studies of large spatial extent (i.e., continental or global), aggregation of model outputs was completed as a post-processing step to simplify outputs to similar hydrological zones. This removed or diminished any effects of regionalizing model input data to a specific model computational scale [78], and the local-scale heterogeneity and errors inherent to distributed models. However, using these regionalized results to develop unit streamflow outputs (i.e., $m^3/s/km^2$) may present several drawbacks, including reduced attention to watershed-specific hydrologic considerations and reliance on absolute values rather than indications of the magnitude and direction of changes to peak flow resulting from climate change.

2.1.3.4 Reference Historical Datasets

A reference historical climate dataset is needed for the modelling chain to support bias adjustment of the GCM variables such that they adequately represent the distribution of historical observed values and can also be used for hydrological model calibration. The reference historical dataset must be a complete gap-filled time series representing, at a minimum, temperature and precipitation values. Reanalysis datasets that provide observed data aligned with model resolution have been developed for this purpose [13]. In Canadian studies it is especially important that the phases of precipitation (i.e., rain and snow) are adequately represented within the historical dataset [49].

The ERA5/ERA5-Land provides an effective reanalysis dataset for hydrological model calibration [79]. ERA5 provides the same variables as the climate models, so it is well aligned for the GCM/RCM bias correction step, and it has been shown to be consistent with, or form the basis of, other global and North American-wide reanalyses used for hydrological modelling [47], [49]. ECCC's RDPA dataset may also be suitable for this purpose [50].

The Water Survey of Canada's hydrometric network provides historical streamflow data at selected locations across the country [80] and represents an important source of data from which to calibrate routed flows at the gauged locations. Hydrometric data in transboundary watersheds may also be required from the USGS. Both Canadian and US data contribute to the World Hydrological Cycle Observing System (WHYCOS), a global network of hydrometric observations under the World Meteorological Organization's HydroHub initiative [81].

2.1.3.5 Local or Regional Impact Assessment

One major issue with existing climate change impact assessments is that the reported time step of the climate ensemble is rarely shorter than daily. Although hydrological routing models simulating historical conditions could include sub-daily time steps, models forced by downscaled climate datasets would be subject to the same coarser resolution as the climate models. The resulting daily time step is, in many cases, too coarse for bridge design peak flow estimation. Further practitioner intervention to convert peak flow estimates from daily to instantaneous values would be required [82]. Methods exist to convert instantaneous peak flows from daily maximums, but these approaches generally rely on historical relationships. The flood hazard delineation guideline published in 2019 by Natural Resources Canada (NRCan) notes that for a single site hydrometric gauge, the period of overlap between daily (Q_D) and instantaneous (Q_P) peak flow measurements can be used to estimate variables *a* and *b* and extend an instantaneous peak flow record [83]:

$$Q_P = aQ_D^{\,b}. \qquad \text{(Equation 1)}$$

Machine learning techniques could also be used to support conversion from daily to instantaneous peak flow estimates [78], [79].

2.1.4 Flood Frequency Analysis

Typically, a flood frequency analysis (FFA) is used to determine the frequency and magnitude of floods (or peak flow thresholds) under stationary hydrologic conditions and can be applied to recorded (observed) historical, modelled historical, and modelled future conditions. "Stationary" is defined in the NRCan flood hazard delineation guideline as applying to both land use and climate-related changes [83].

Should the complete record of flow observations inadequately represent the tails of the distribution (i.e., extreme flow scenarios) or be too short (< 10 years according to [83]), then a probability distribution that best represents the distribution of the data should be used to statistically estimate the extreme values. Commonly used distributions for FFA include Gumbel, log-normal, log-Pearson type 3 (LP3), or generalized extreme value (GEV). The chosen distribution is then fit to the observed (or modelled) data using statistical techniques, such as the method of moments or maximum likelihood estimation, to assess the fit of the distribution moments (mean, variance, skew, and kurtosis). Generally, the GEV and LP3 distributions are found to be the most representative of Canadian observed hydrometric records [84], [85], and are consistent with the recommendations in the NRCan guideline [83].

In a stationary climate, the return period (T = 1/AEP) for various flood magnitudes and the uncertainty bounds can be determined from historical records, regionalization of flows, and watershed modelling. The NRCan flood hazard delineation guideline lays out the following recommendations and considerations for FFA [83]:

- The use of instantaneous peak flows is preferred over daily maximum.
- The preferred record length should be at least ½*T with the minimum record length being 10 years for statistical viability [86].
- Missing peak flow data should be infilled using relational techniques.
- Homogeneous data, such as those having similar flood generation mechanisms (snow vs. rainfall generated peak flows) should be grouped.
- Extreme high flows may need to be considered separately, as part of a different distribution.
- Records significantly impacted by land use and water management changes (i.e., non-stationary) should be excluded or naturalized to a common base.

It is important to evaluate streamflow stationarity over the periods of analyses, and in many cases, selection of a shorter time period may be necessary to avoid breaking the assumption of stationarity underpinning the statistical methods. In these cases, methods accounting for non-stationarity in FFA can also be used [87], [88], [89]. Lessons learned from the probable maximum precipitation literature and applications suggest that consideration of compounding factors generating extreme events is critical, and instantaneous data should be used where possible to generate true maxima [90].

The process of estimating peak flows at a site typically involves performing an FFA on observed or modelled flows to determine the flood at a desired return period (i.e., AEP). In the case of a climate change impact assessment, modelling is necessary, and understanding the range of potential outcomes requires the use of model ensembles. Consequently, the results are typically presented as a range of potential flows for each AEP.

2.1.5 Considering Climate Change Non-Stationarity

Before climate-informed hydrological modelling of the watershed can commence, the model must be calibrated and verified against observed streamflow. This is typically completed using a historical dataset (i.e., reanalysis dataset) representing a baseline time period, suitable for the scale of the watershed and resolution of the climate scenarios. Climate scenarios are then used to force the hydrological model to produce a continuous time series overlapping the historical reference time period and extending into the future.

The simulation is completed for each member of the climate ensemble, generating multiple realizations that represent a range of projected hydrological conditions. From the model ensemble, the historical and future period results represent a range of possible outcomes that in their entirety encapsulate the mean, variability, and uncertainty associated with potential flow values. Ideally, the FFA based on the observed historical period would match the FFA based on GCM-driven historical results with respect to at least the mean and variability of the FFA distribution, or the distribution moments [87].

When considering flood frequency in a non-stationary climate, the FFA becomes fundamentally dependent on time; different FFA results will manifest for the same location, depending on the period being analyzed [89]. Notably, flood quantiles have to be estimated from a sample of non-stationary streamflow data, a process for which traditional FFA tools are unsuitable. A common approach to resolve this problem is to break the data into blocks of time (i.e, climate windows) and assume that within each period the resultant data (i.e., peak flows) are stationary (see https://climatedata.ca/interactive/30-years-data/). This allows the FFA to be conducted independently within each climate window. The downside is that the resulting sample size can be small (e.g., n = 30 years) if the analysis is conducted individually for each ensemble member. The sample size can be increased by pooling data across ensemble members, but if each member represents a different model or scenario, then the data may not be identically distributed. Using a SMILE solves this problem by allowing data to be pooled across a large number of simulations, with the added benefit that the resulting sample size is typically large enough that empirical methods can be used to estimate quantiles. The trade-off is that the results do not reflect all the elements of uncertainty, such as model structure uncertainty and the full range of possible climate futures.

Several other options can also be considered. For example, using a temperature threshold instead of time to define the sample period may present an opportunity to pool data across models. Specifically, if peak flow magnitude scales with temperature the same way across models then the response to climate forcing at each temperature threshold will be model and scenario agnostic. This approach would also capture a wider range of uncertainty due to model structure and emission scenarios. However, guidance for bridge design must consider the design life of the structure and the peak flows that could be expected over this period, which are dependent on the emission scenario.

Non-stationary FFA approaches can also resolve the stationarity issue, allowing for a full suite of time series projections to be pooled into the same analysis. Distribution parameters use time or global mean temperature change as a covariate, and flood frequency curves can be fit to individual ensemble members using the full period of record.

Notably, FFA could be performed on the multiple ensemble datasets to estimate future condition peak flows and to evaluate the impacts of climate change over the periods of interest or relative to temperature thresholds. Alternatively, for the purposes of understanding the magnitude and direction of change, the relative difference between historical and future condition peak flows can be determined based on selected quantiles.

"The methods presented in the NRC report, an Ouranos report, and a study by Gillett *et al.*, provide the most guidance in terms of rigour and feasibility for future studies to derive Canada-wide bounding curves for peak flow assessment."

By selecting discrete increments of °GMT rise for evaluating future peak flows, the time horizons and relative changes in peak flow can be estimated irrespective of when that occurs. This approach is favourable because it allows for adaptive design considerations as climate uncertainty becomes better understood [85].

2.1.6 Best Practice in Canadian Peak Flow Estimation

The methods presented in the NRC report [31], an Ouranos report [91], and a study by Gillett *et al.* [92], provide the most guidance in terms of rigour and feasibility for future studies to derive Canada-wide bounding curves for peak flow assessment. The NRC and Ouranos reports lay out methodologies required by practitioners to conduct climate change impact assessments [31], [91]. A summary of the approaches and lessons learned from each of these studies is presented in this section.

The NRC report examined **floods in Canada for planning and design purposes** [31]. Its objective was to reduce the impacts of natural disasters in Canada with a focus on floods. The report reviewed national and international studies and summarized a variety of approaches for modelling climate change for the purposes of flood plain analysis. An inventory of approaches is detailed to provide a set of guidelines and recommendations for practitioners in Canada. The final recommendations listed in Chapter 5 of the NRC report formed the basis of the elements discussed in this report, including study scope, elements of climate model and emission scenario selection, time horizons for analysis, downscaling and bias adjustment procedures, and the downstream modelling chain (e.g., considerations of hydrologic and hydraulic models).

The Ouranos study was undertaken to **estimate flood frequency for dam safety applications,** extending to 2100 [91]. Similar to the NRC report, it synthesized important procedural elements or steps taken for the purposes of FFA to capture climate-impacted peak flow estimates for dam safety. Of particular importance was the post-processing of the hydrological model outputs to derive the FFA estimates and peak flows. The project was divided into three different working groups (WG1, WG2, and WG3). In the context of this research report, the outputs of WG1 are particularly relevant, as they are intended to be "simple enough" for practitioners, but still of sound methodology. WG1 considered the scaling of events, mixed events, and routing/storage and attenuation effects impacting watersheds. They used a Kling–Gupta efficiency of 0.61 as a minimum model performance criterion for watershed inclusion and applied two LEs (CanESM2-LE and the Community Earth System Model, CESM1-LE) for RCP 8.5 to drive a simple lumped, 5-parameter GR4 hydrologic model. Notably, the RCP 8.5 scenario did not always produce the maximum streamflow due to snowpack changes.

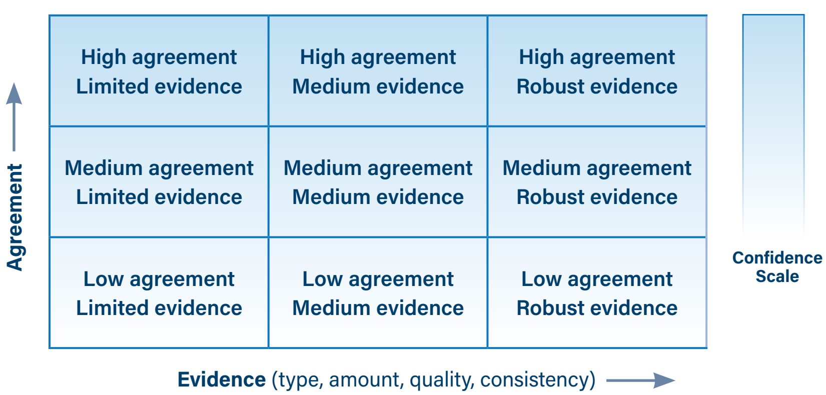
The GEV distribution was used (though a lack of agreement was noted) because it was considered to be the only distribution that could extrapolate to unobserved extrema. Maximums were computed over 20 x 5-year blocks to estimate the 1,000-year and 10,000-year flood peaks. The Ouranos report provided guidance on the FFA decisions from climate ensemble output presented in this report.

The study by Gillett *et al.* was a **post-flood event analysis** of the November 2021 flooding that impacted British Columbia's Fraser Valley, threatening public safety and causing extensive damage to transportation, infrastructure, and agriculture systems, as well as to the livelihoods of people in the Sumas Prairie region [92]. This study was completed under a strict timeline (limited computational time) in order to provide guidance for post-flood recovery. The watershed analysis was limited to runoff only (i.e., no flow routing), a single hydrological model (VIC), and basins with minimal regulation or alteration effects (i.e., stationary land cover). The study used CanESM2-LE (50 members, RCP 8.5) as forcing data, with the goal of assessing climate-impacted changes to the flow duration curves and anticipated future peak flows from hydrologic change driven by internal climate variability. Design flood values were provided for the following 30-year blocks: 1961–1990, 2010–2039, 2040–2069, and 2070–2099.

2.1.7 Consideration of Uncertainty

The cumulative effects of the modelling chain increase uncertainty in estimating peak flows under a changing climate. Sources of uncertainty include those previously discussed in climate modelling: structural uncertainty, internal climate variability, and emissions scenarios [93]. Additional uncertainties are encountered with impact models that relate to downscaling techniques, bias adjustment, hydrologic model selection, model resolution (i.e., temporal and spatial), hydrologic model data sources (i.e., geofabric), and model calibration and verification. While most of these uncertainties can be quantified, it is often at the expense of increased data conditioning and computational effort [94]. For example, hydrological models that represent more physical watershed processes may improve representation of the variable hydrological conditions that exist across Canada, but their complexity often requires additional model parameters to represent these processes. As shown in Figure 2, the IPCC introduced a qualitative framework for reporting uncertainty and assessing the overall confidence in projections derived from ensembles in their AR5 guidance note, which could be particularly useful for practitioners. In this way, depending on the number of scenarios (i.e., amount of evidence) and agreement among the projections, a relative

Figure 2: IPCC (a) assessment of multiple lines of evidence to determine overall confidence, which can then be translated to b) the likelihood scale to describe quantified uncertainty. from the AR5 [89]. Reproduced from [27], European Environment Agency.



Likelihood Scale	
Term*	**Likelihood of the Outcome**
Virtually certain	99-100% probability
Very likely	90-100% probability
Likely	66-100% probability
About as likely as not	33-66% probability
Unlikely	0-33% probability
Very unlikely	0-10% probability
Exceptionally unlikely	0-1% probability

confidence can be determined and transcribed into a likelihood measure [27], [95]. The IPCC methods were adopted by the Canada's Changing Climate Report 2019 [8]. Similarly, the Climate-Resilient Buildings and Core Public Infrastructure report adopted a tiered approach (1, 2, or 3) that corresponds to confidence in future projections [28].

2.2 Relevant Research Activities across Canada

In addition to the literature review presented in Section 2.1, a review of existing research initiatives and research and development projects across Canada designed to improve peak flow estimation and Canada-wide modelling was also undertaken. Four initiatives of interest were identified and are discussed in sections 2.2.1 through 2.2.4.

2.2.1 Flood Hazard Identification and Mapping Program

The Flood Hazard Identification and Mapping Program (FHIMP) was launched in 2021 and is led by NRCan [96]. It has two key components: the development of flood prediction tools (academic, University of Calgary, Principle Investigator: T. Stadnyk), and the development of floodplain maps (Natural Resources Canada and consultants, subcontracts). The first component includes predicting flow in a changing climate, which is relevant to this report, and includes developing:

- Standardized workflow for non-stationary trend and FFA; and
- Non-stationary (climate change impacted) peak flow estimation tool using stochastic modelling methods that use open-source R software.
- Notably, a key aspect of the second component, development of flood hazard maps, relies on prediction of peak flows under various hydrological conditions, which aligns with the needs identified in this report.

2.2.2 FloodNet Regional Frequency Analysis Toolbox

The FloodNet Regional Frequency Analysis (RFA) toolbox was a deliverable of Canada's Natural Sciences and Engineering Research Council (NSERC) FloodNet project. The RFA toolbox is a freely available open-source R-script with a graphical user interface that was specifically designed to support engineers and practitioners in performing efficient FFA [97]. Functionalities include analysis of flood discharge annual maxima, peaks over threshold (POT) analyses, and prediction at ungauged sites. The FloodNet RFA toolbox includes:

- Free supported software for the Canadian community;
- Bounding curves, or uncertainty envelopes, at the RFA locations of interest;
- Applicability to watersheds with no hydrometric gauges (i.e., ungauged basins); and
- POT statistical analyses to account for different flood-generating mechanisms [98].

While the toolbox does not provide future climate-adjusted peak flow assessment, it is relevant to this report because it includes standardized approaches for RFA, an efficient methodology with a graphical user interface, and a potential platform for assessing climate-adjusted peak flow frequencies.

2.2.3 Downscaled and Bias Corrected Climate Ensembles

Work by the pan-Canadian Global Water Futures research program [99] to support modelling efforts across Canada facilitated the dissemination of bias corrected and downscaled CMIP6 simulations, totalling 160 simulations (i.e., 40 models, 4 emissions scenarios). The data includes Canada-wide minimum and maximum temperature and precipitation, with a multivariate bias correction.

Considerable effort has also been invested by government agencies, entities, and academics to produce Canada-wide LEs derived from the CanESM2 model (i.e., CanESM2-LE) that are downscaled using the Pacific Climate Impacts Consortium (PCIC) bias adjustment techniques to support hydrological-scale assessment. These are available and disseminated through Canada's climate consortiums (i.e., Ouranos, PCIC) or ECCC, each with a slightly different bias adjustment baseline dataset. The use of a single climate model and emission scenario will reduce the projected spread of simulations and outcomes by considering only the internal variability independent of emission pathways. The large ensemble associated with a single climate model typically encompass one GCM or RCM with different initial conditions [33] and boundary conditions.

Ouranos has also developed a generic scenario dataset called ESPO-G that removes hot models from the ensemble [100]. There is also a version available that is corrected to ERA5 called ESPO-G6 [101]. Bias correction using the RDPA is also commonly applied across Canada as a viable alternative [102].

2.2.4 Model Agnostic Framework

Under the Global Water Futures core modelling program [103], work is underway to generate and produce standardized modelling workflows and supporting tools for the Canadian, North American, and ultimately, the global community, that are applicable to climate modelling and impact studies. The anticipated completion date for this program is March 2024. Not only can lead to greater consistency and expectations for modelling studies undertaken by practitioners, but it also aims to provide the following additional benefits:

- A priori geospatial data processing (i.e., the geofabric for the hydrologic model, including a digital elevation model, land cover data, soil classification data, and hydrography) for all models and all sub-basins across Canada commensurate with the HUC4 classification [32];
- An interface for complex, physically-based process models (i.e., SUMMA, WATFLOOD, HYPE, and MESH), facilitating multi-model ensemble analyses;
- A means of integrating new toolboxes to improve hydrological model consistency across the entire modelling community;
- Scripts and standards for model benchmarking (evaluation) to ensure consistency;
- Documented workflow and expectations for modelling studies [104]; and
- A stand-alone vectorized routing product, MIZUROUTE, that includes regulation and can be interfaced with any gridded data product.

This framework can facilitate a reproducible workflow that is consistent between development of the bounding curves and delta-change factors under this research report, and by practitioners undertaking independent, detailed watershed-specific hydrological analysis for a bridge site.

2.3 Practitioner and Agency Interviews

Representatives from fifteen agencies across Canada were interviewed to gather a range of input and advice related to climate-adjusted peak flow estimation. The interviewees were selected to represent diversity in sector (e.g., government at various levels, industry, and consultants), geography (e.g., west to east and north), and size of organization (e.g., large, multi-employee organizations to single-person firms). Interviewees' comments were captured by the project team and considered in the recommended approach put forth in this report.

Potential practitioners and agencies were selected based on their active involvement in peak flow estimation and with consideration of regional representation, as shown in Figure 3. Interviews were conducted with experts who accepted the invitation to participate, and typically lasted approximately one hour. A summary of the responses is provided in Table 2 as items of emerging consensus (i.e., >80% of practitioners agreed) and items of emerging concern, as emphasized by individual agencies or practitioners. The interviewees agreed that the initiative was long overdue and represented a worthwhile investment. Practitioners also agreed that the bounding curves and resultant delta-change factor approach could provide a valuable tool to support peak flow assessment in a changing climate.

One significant concern centered around the level of effort required to conduct the national scale peak flow initiative, with interviewees noting that modelling all watersheds across Canada under a variety of climate scenarios would take a substantial amount of time and funding. Interviewees noted that a previous suggestion, which relies on using a compilation of results from existing studies (see Section 2.2) to develop bounding curves of peak flows, presents considerable risk because of differing study foundations (i.e., ensembles, climate model scenarios, time periods, bias adjustment, calibration, etc.), which all affect the uncertainty envelopes and have the most substantial impact on the upper quantiles (i.e., AEP < 0.01; RP > 100 years). Other concerns emerged around the definition of small watersheds that are suitable for applying rainfall-runoff methods, regional scale-dependence, and the definition of hydrological zones. Concerns were also expressed that this effort might usurp the role of hydrologists and exclude the expert knowledge that they bring to varying geographies and climates across the country. Finally, interviewees noted that this simplified approach could impede the development of improved tools and research by local practitioners.

Figure 3: National representation of agencies and practitioners interviewed for this report.

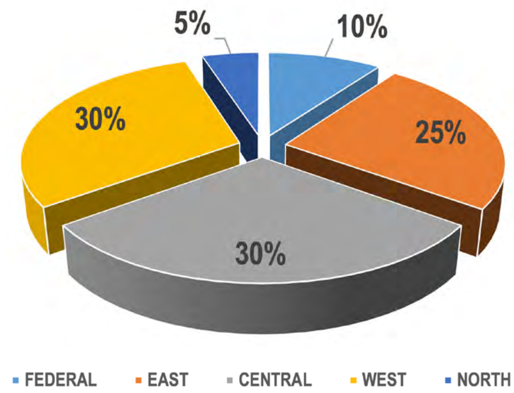


Table 2: Summary of feedback from interviewees as items of emerging consensus and concern

Emerging Consensus[1]	Emerging Concerns
A simplified, but conservative approach is needed that provides guidance/tools for practitioners that do not have time, money, or capacity for climate-informed FFA. Huge discrepancies in quality, components, and approach of existing modelling studies present a risk to deriving bounding curves from existing reports/studies. Ignoring flow regulation (i.e., reservoirs) is likely okay because it is generally conservative and accounts for extreme conditions where high peak flows (AEP < 0.01; T > 100 yr) may not be significantly attenuated. Using a SMILE, single RCM methodology to estimate peak flows under climate change is considered "good enough" under limited resourcing and could be selected over a multi-model ensemble. Empirical (best fit to the data) or GEV distribution are favoured approaches if an FFA distribution is used. Under large ensembles, empirical distribution is acceptable for AEP < 0.01 (T > 100 yr) and likely acceptable for AEP < 0.02 (T > 50 yr). The small watershed threshold should not be defined solely based on drainage area but should consider the nature of the watershed and expected hydrologic response. Time of concentration may be the most useful indicator of the minimum applicable watershed size. Extreme rainfall tends to be underestimated by GCMs and even RCMs. Expert hydrologist opinion and local knowledge is invaluable in guiding the peak flow assessment and should be a key factor in the approach and methodology. The level of effort required to reduce uncertainty in hydrologic prediction should be related to the criticality and consequences of damage to the bridge structure. Achieving complete consensus on all aspects of the approach is unlikely to be achievable. Any national scale standard for climate change-informed peak flow analyses will take time and significant effort, but that is wanted and needed.	Defining the size of a small watershed (i.e., where the Clausius–Clapeyron equation can be applied to rainfall-runoff methods and therefore excluded from the initiative) remained unclear. The small watershed threshold ranged from 5–100 km^2 with most stating < 50 km^2. A Quebec study indicated that rainfall-runoff methods such as the rational method should be limited to areas < 100 km^2 [105]. If used to develop bounding curves, consistency among climate studies would be very important (i.e., bias adjustment, calibration data, climate scenarios, time periods, etc.). Ideally, everything will be modelled under one study. It will be unlikely to find a one-size-fits-all FFA distribution that represents all watersheds. It will be difficult to achieve consensus or find agreement on regionalization or hydrologic zones for watersheds across Canada. Localized/single watershed extreme events or broad scale multi-watershed or compound events tend to result in extreme scenarios; hydrological models are often poor at estimating these. Avoid regionalization approaches. It is better to maintain a sub-basin database. This would be more useful and transparent to practitioners. Providing a national dataset of bounding curves and delta-change factors might detract from local knowledge and practitioner expertise. Consider cases of diversions as a separate type of regulation, particularly if peak flow can increase above naturalized conditions. Acceptance of bounding curves and delta-change factors will require them to be realistic and not attempting to incorporate all climate change considerations and uncertainty (i.e., include a statement of limitations).

Note. [1]Consensus was defined as >80% of agencies or practitioners highlighting or reporting the same information in the interview.

3 Toward a National Dataset of Bounding Curves

All watersheds are unique and vary in complexity. As such, it is important to recognize that applying practitioner knowledge can capture the unique characteristics exhibited by any watershed, which reduces inaccuracies and uncertainties related to historical and potential future hydrologic responses. However, the CHBDC [1] would benefit from more clearly defined hydrological requirements to estimate peak flows at bridge sites. Methods should distinguish between the hydrological response of watersheds, and in particular, if the peak flow generated can be reasonably predicted based on rainfall-runoff approaches that rely on IDF curves. A distinction between small and large watersheds could be made, with the former being guided by rainfall-runoff methods and the latter requiring climate-informed watershed modelling. However, watershed modelling driven by historical and future climatic variables is labour intensive and the effort may not be commensurate with the risk associated with a bridge structure. Therefore, a methodology that allows practitioners to use a simplified, conservative adjustment factor that can be applied to current climate condition peak flow estimates is envisioned.

Development of watershed-specific delta-change factors based on a model-to-model comparison of historical and future condition peak flows provides several benefits compared to a unit runoff approach that provides a flow value per contributing area. Two compelling reasons are put forward to support a delta-change factor approach:

1. Practitioners would need to consider the unique characteristics of each watershed in order to complete a current condition FFA based on observed data and/or other traditional methods of peak flow assessment; and
2. A modelled historical to modelled future peak flow comparison may result in a higher trust factor compared to an absolute value, such as a unit runoff approach, which requires practitioners to put their faith in a "black box" model.

Despite the potential change in peak flood-generating mechanisms, practitioners should use historical records and traditional FFA approaches to understand current conditions as the basis for any peak flow assessment. In the context of the initiative, it is only after the historical hydrological assessment and FFA is completed by a qualified person that the bounding curves should be considered, and the delta-change factors be applied. This approach supports using practitioner knowledge and existing information while considering the changes that may occur over the design life of a structure.

While any contemplated updates to the CSA CHBDC S6:19 [1] should encourage bridge owners and practitioners to complete watershed-specific hydrologic assessments, the application of delta-change factors to historical FFA values is an acceptable, albeit conservative alternative. It is important to note that the proposed approach is not intended to discourage practitioners from completing climate-informed watershed hydrologic peak flow assessments or site-specific historical peak flow FFA. Rather, the proposed approach would require that practitioners complete the historical FFA for the bridge site using traditional methods. This would establish historical baseline peak flows and understanding of the critical peak flow mechanisms (e.g., rainfall, snowmelt driven), which would allow the practitioner to consider all hydrologic complexities related to a specific site, including watershed characteristics and flow routing. The bounding curves and related delta-change factors can then be applied to the historical peak flow FFA while working within the stated limitations and specific guidance.

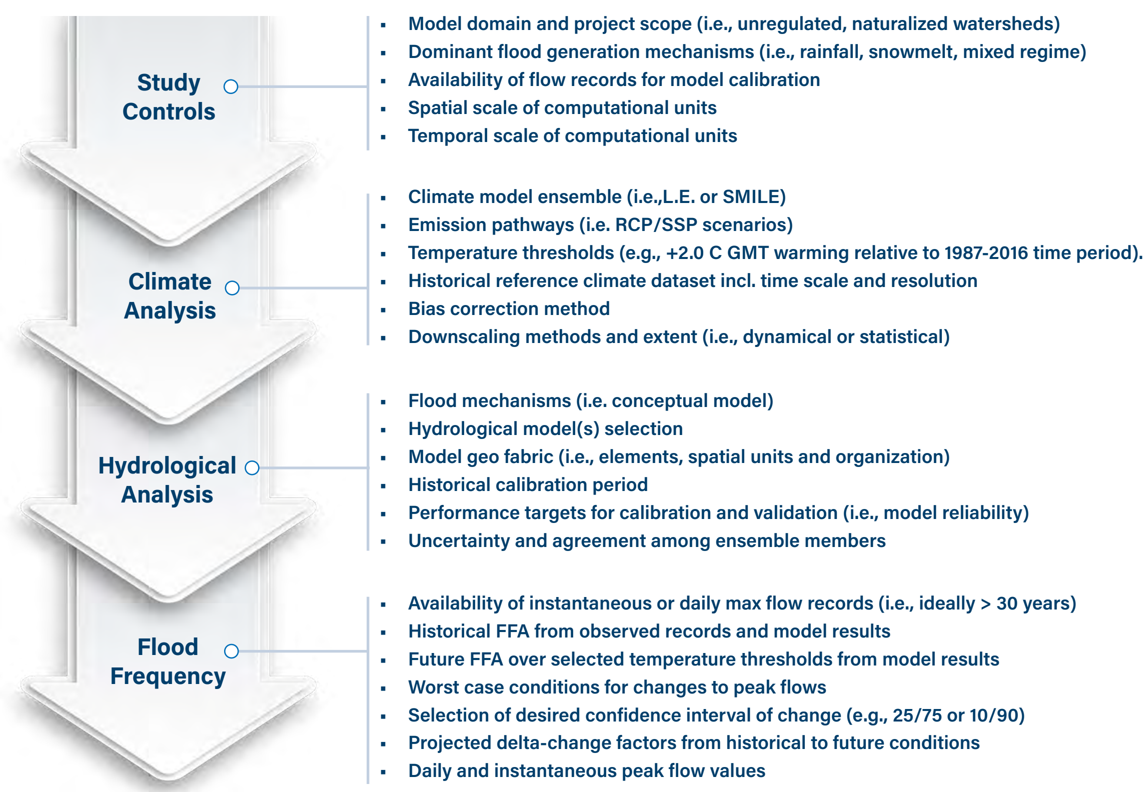
A national database of bounding curves would document the projected change from natural/naturalized historical to natural/naturalized future peak streamflow resulting from climate change for watersheds across Canada. Under the initiative, uncertainty envelopes produced from the climate ensemble would allow selection of conservative delta-change factors from a range of projected flows. Delta-change factors would represent a set of confidence intervals of expected change when comparing current to future peak flows over the design life of a bridge. Practitioners would apply the delta-change factors to current condition at-site peak flow estimates to adjust peak flow values to account for the impacts of climate change.

The literature review identified several existing initiatives that can be leveraged to support or dovetail with a Canada-wide modelling effort to derive bounding curves and delta-change factors that quantify the expected changes that could occur when comparing historical baseline peak flow estimates against future condition peak flow estimates. The key considerations for each stage of development of a national dataset of bounding curves and delta-change factors are outlined in Figure 4.

To derive bounding curves and develop delta-change factors to estimate at-site climate-affected peak flow for each modelled **sub-basin** across Canada, the following data needs to be generated:

- **Ensemble of climate model output** that are bias adjusted to a historical climate reference dataset and downscaled for, as a minimum, temperature and precipitation and extend from the reference historical period through the future climate period. A range of threshold global warming temperature changes would be used to define climate periods in the bounding curves and to develop delta-change factors.
- **Hydrological model(s)** calibrated to the same historical reference climate dataset used for bias adjustment of the climate models, evaluated against observed streamflow data over a historical baseline reference period. The focus would be on the magnitude and timing of peak flows at the finest temporal resolution practical (i.e., daily).
- **Modelled timeseries of streamflow** for both historical and future periods (e.g., 1987–2100), driven by a climate ensemble but with consideration of independent emission scenarios that would produce an uncertainty band of projected historical and future

Figure 4: Key considerations for development of Canada-wide delta-change (Δ) factors.



streamflow. The uncertainty band would allow estimates of the maximum expected changes to peak flow over the simulation period.

- **Bounding curves** that compare the range of historical (i.e., 1987–2016) and future peak flows in representative watersheds across Canada. **Delta-change factors** would be derived from the bounding curves based on the offset of the historical and future projected peak flow at incremental changes in GMT rise and selected confidence interval (e.g., 25^{th} percentile for historical and 75^{th} percentile for future).

To estimate peak flows over the design life of the bridge, at-site **historical FFA** would be completed by a qualified practitioner using traditional methods, such as single station frequency analysis, regional approaches, or hydrological modelling. A variety of annual exceedance probabilities ranging from 4% to 0.2% may be required to evaluate scour and erosion and to estimate design flood discharge. These represent the base values to which the appropriate delta-change factor(s) would be applied.

3.1 Recommended Approach to Develop a National Bounding Curve Dataset

Figure 5 illustrates the proposed steps to generate a national dataset of bounding curves that could be used to develop delta-change factors. Suggested best practices for each step are described in sections 3.1.1 through 3.1.11.

3.1.1 Define Study Scope

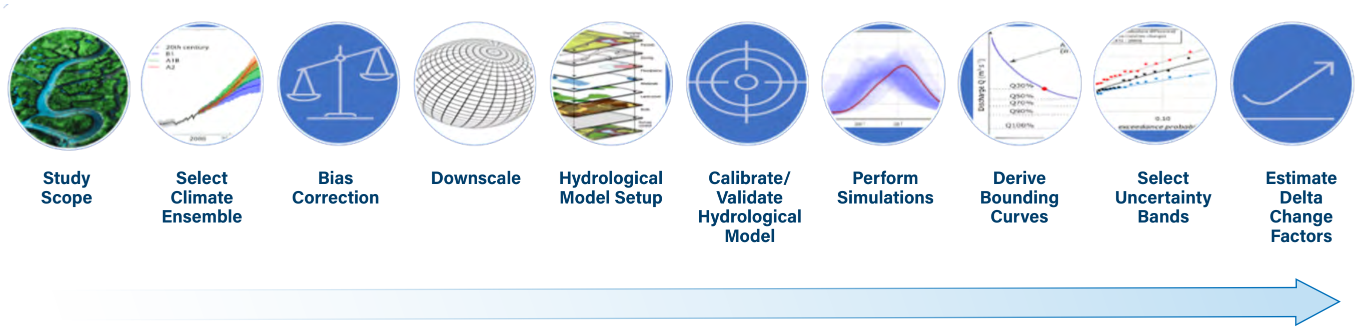
For the purposes of the initiative, the domain of interest is Canada-wide. However, bounding curves would be derived from specific natural watersheds that have appropriate flow records. Candidate watersheds should be pre-screened to ensure they meet the following criteria: minimally regulated, sufficient observational records, and relatively stationary through time.

Enhanced screening criteria should be developed to determine which basins and sub-basins are included or excluded from the analyses. Enhanced criteria to be considered include:

- Supports development of a database that represent watersheds governed by varying runoff mechanisms and hydrological response;
- Contributes to spatial coverage of various climatic and geographic landscapes of Canada;
- Includes sufficient observational records (i.e., minimum of 10-years of homogeneous flow records); and
- Experiences minimal natural and anthropogenic changes in watershed (i.e., assumption of stationary is valid).

Following watershed selection and calibration, the decision to expand model simulations to ungauged basins could be reviewed, but minimal flow regulation and watershed stationarity conditions will still need to be met.

Figure 5: Workflow for the derivation of a national dataset of bounding curves and delta-change factors.



It is recognized that comparison and aggregation of results could support the definition of hydrological regions and application of delta-change factors in a simplified manner for practitioners. However, the delineation of hydrological zones or regions is a source of debate and could represent a loss of information at the individual basin scale and is therefore not included in the initiative. If included at a later time, several flood frequency studies provide guidance on similarity of flood generation mechanisms [8], [95], and on Canada-wide runoff generation mechanisms [55] and hydrologic processes [106]. Furthermore, reanalysis data and remotely sensed data could provide information on climatology gradients. A classification commonly used for hydrology includes adapted versions of the Köppen-Geiger classification [105].

3.1.2 Climate Model Ensemble Selection

At the time of writing, the state-of-the-art for climate models is CMIP6 and the production of downscaled regional simulations across the Canadian domain (e.g., CESM1 and CanESM2). CMIP6, comprised of numerous GCMs from a variety of institutes [12], provides information with respect to model structural uncertainty (and natural and internal variability from multiple simulations of the same GCM) as well as climate scenario uncertainty, spanning different SSPs [107]. While large ensembles developed from SMILEs across the Canadian domain (e.g., CanESM-LE and others) are generated to describe the natural or internal variability separate from the forced (emission trajectory) impacts, they represent a reduced level of total uncertainty. They should also leverage downscaled models (i.e., RCMs) representative of the Canadian domain [18], [108] or the North American domain [109]. It is expected that the climate variations (uncertainty) from a CMIP6 ensemble would be greater than those represented by a SMILE. Although a SMILE can offer a more precise projection of change under a given scenario for a specific region of interest, it may not fully capture the range of outcomes and extreme events suitable for peak flow estimation.

To capture the full range of climate uncertainty, multiple representations of future climate are needed, if computationally feasible. Ideally, the ensemble should include multiple GCMs/RCMs and variable initial conditions (i.e., members). The goal is to select a climate model ensemble that provides the full range of possible outcomes over the region of interest to allow assessment of key parameters, including the mean value and variability of results. Contrary to Section 2.1.3.1, where a single emission scenario and time frame is considered, this approach may not capture the worst-case condition for peak flow assessment over the design life of a bridge. The time frame for each emission scenario to cause a specified rise in °GMT, along with its associated hydrological response, will vary depending on the scenario. As such, model simulations would benefit from treating emission scenarios independently.

Both historical and future climate should be simulated using the climate model ensemble, as it is important to compare model-to-model results rather than comparing observed historical to modelled future conditions, which would introduce another level of uncertainty (see Section 3.1.4).

Though standard future time horizons are often applied in the literature to examine changes in future climate and hydrology, the IPCC AR6 recommends selecting a temperature rise threshold (i.e., GMT rise of +2.0°C) for evaluating climate mitigation and adaptation effects [107]. Given the design life of bridge structures is typically 75 years, Table 1 (see Section 2.1.3.1) focuses on +2.0°C GMT rise relative to a baseline period (i.e., 1987–2016), which is anticipated under RCP 6.0 to be reached by 2087. Reliability will be increased by using multiple GCMs/RCMs and initial/boundary conditions. However, uncertainty may be increased by including potential hot models. If only one emission scenario is considered based on the above assumption and selection of a SMILE, then uncertainty will be reduced, but reliability (chance that the projected future design flow is captured by the ensemble) will also be reduced. Inherent to the consideration of what type of climate ensemble should be selected is the level of accepted risk and the computational constraints of bias correcting and downscaling the climate ensemble for all of Canada. To that end, if possible, other projects should be leveraged to increase efficiency but still meet the accepted and perceived risk levels for developing bounding curves and delta-change factors for peak flow estimates.

"To capture the full range of climate uncertainty, multiple representations of future climate are needed, if computationally feasible."

3.1.3 Bias Adjustment of Climate Data

To ensure climate models adequately represent the range of potential conditions for use in hydrological studies, they need to be adjusted closer to the known, historical observed climate over the areas of interest. While temperature and precipitation are the minimum hydrological variables required from the climate models, selected hydrological models may require additional variables. Given the size and scope of the initiative, statistical downscaling is recommended. Multivariate (i.e., adjusting temperature and precipitation in unison) bias adjustment should be used to help ensure the correlation structure of the primary hydrological inputs is preserved [45]. The historical reference climate dataset selected for bias adjustment should be commensurate (i.e., the same or same statistical properties) with the historical dataset used for subsequent hydrological model calibration. Another consideration in selecting a historical reference climate dataset is the spatial coverage of transboundary watersheds. In other words, any dataset selected for bias correction and model calibration will need to be North America wide, or at least include the transboundary watersheds spanning the Canada–US border.

3.1.4 Downscaling of Global Climate Model Data

GCMs describe global climate at coarse resolutions (100–500 km) and must be downscaled to more accurately represent the atmospheric-hydrologic feedback mechanisms of Earth's surface for a more realistic representation of hydrology (e.g., temperature, evapotranspiration). Regional climate-hydrologic interactions are needed. For the initiative, these will likely be best achieved using statistical downscaling to 4–25 km spatial resolution. This would afford consideration of Weather Research and Forecasting model convective-permitting simulations and Earth system models (e.g., CanESM2) for Canada and North America. The data, previously downscaled, is available from Canada's climate consortiums (e.g., PCIC or Ouranos) across a range of SSPs or RCPs. Any future work should leverage previously completed efforts to the degree practical, not only for consistency among studies and practitioner applications in Canada, but also due to computational effort and resources.

3.1.5 Hydrologic Model Selection

Hydrological model selection is important because it will affect the spatial resolution (i.e., hydrologic response unit, or HRU, gridded) of input and output, temporal resolution, data needs, ability to represent hydrological processes, runoff generation mechanisms, and computational demand. It is unlikely that a single model can effectively represent all regions of Canada, so it is important to establish and report model selection criteria. Regardless of the selected model, computational demand will be significant, so it is important to balance the level of effort with the uncertainty and reliability of the model results. Minimum requirements that should be met include:

- Temporal resolution: daily time step; and
- Spatial resolution: ~100 km^2 (10 x 10 km^2 grids, or similar HRU).

Gridded distributed model outputs are not necessarily required for this initiative. A lumped, sub-basin model is likely to perform equally well or better than a gridded, distributed model, due to the regionalization of climate data (assuming adequately high resolution, commensurate with RCM grids, on average). This broadens the choice of potential hydrological models.

Due to computational demands, every effort should be made to leverage existing model setups and products, assuming they are consistent with the project scope and needs. The FHIMP initiative presents an opportunity to leverage an existing ensemble of hydrological models with demonstrated success in Canada [96]. This ensemble includes three distributed hydrological models: HYPE, MESH, and SUMMA. These models can generate gridded and sub-basin runoff under historical and future climates that are all routed by a single, consistent vector routing product that includes lakes and reservoirs consistent with their representation in the CanESM [110], [111]. By aligning this effort with the FHIMP initiative, peak flow estimates can be generated in a manner consistent with the model outputs used to generate Canada's high-level floodplain maps [96]. This would be desirable for practitioners concerned with both bridge design and flood hazard studies. Consistency in the routing method is particularly important for the timing and magnitude of peak flows. The routing used for the FHIMP initiative includes some representation of the influence of natural storage (i.e., lakes) and their attenuating effects on downstream peak flow generation, which is an important consideration for estimating peak flows in Canada. A hydrological model ensemble is preferred because it captures hydrologic model structural uncertainty in the development of bounding curves, whereas selection of a single hydrologic model assumes the uncertainty of the hydrologic model on peak flow prediction would be encompassed within the climate model uncertainty bounds.

3.1.6 Hydrological Model Setup

Hydrological models are designed to represent the generation of runoff across the land surface, and therefore also represent the generation and routing of streamflow in rivers and through lakes [112]. Selection of the geofabric underpinning the study is an important consideration for model setup because the spatial resolution of the RCM data will largely determine the basic computation unit size of the hydrologic model (i.e., grid or sub-basin size), and will impact the accuracy of the model [113]. The time step of the hydrological model is largely determined by the reference climate (i.e., reanalysis) dataset and should be a maximum of daily for peak flow assessment. While hourly or sub-hourly temporal resolution would be most desirable for peak flow assessment, derivation of this data is not likely computationally feasible across the model domain. Therefore, an adjustment from daily to instantaneous peak flow may need to be made following the future condition FFA. Development of instantaneous to daily (I/D) ratios to accompany the delta-change factors is desirable but is outside the scope of this report. Until climate-informed I/D ratios are developed, practitioners are reliant on historical records to assess instantaneous peak flow values, and would likely assume that these ratios do not significantly change in a future climate.

Some practical considerations for hydrological model setup include:

- Climate model time step reporting is typically limited to daily resolution, so the hydrologic model to develop bounding curves would not support sub-daily temporal resolution;
- Delta-change factors would be developed by comparing model-to-model results of current daily peak flow estimates to daily future peak flow estimates over their respective climate windows;
- Historical peak flow assessment would be completed by a qualified person who could include instantaneous peak flow estimates; and
- Delta-change factors representing daily current to daily future peak flow assessments would be selected and applied to the peak flow estimates derived by a qualified person.

For process-based accuracy, which is important for runoff generation, using a distributed hydrological model capable of capturing spatial heterogeneity that includes elevation, land cover, soils, and other physiographic factors is recommended. It is also essential to have good flow records upon which to calibrate and validate the hydrological models across the country.

3.1.7 Hydrological Model Calibration and Validation

Calibration of hydrological models sets or tunes the model parameters to adequately represent the observed flow time series and runoff generation processes within the watershed or domain of interest. Calibration of a hydrological model requires a minimum 15-year time series to capture decadal hydroclimatic variability (e.g., the Pacific Decadal Oscillation and the El Niño Southern Oscillation), and ideally includes the presence of an observed, natural (non-regulated) hydrometric time series at gauge locations across the domain of interest [114]. Because bounding curves are being derived for extreme events (annual exceedance probabilities of 0.2% to 4%), an adequately large sample set covering the climate period of interest should be developed. Satisfactory model performance should be globally achieved across these unregulated basins (e.g., Kling–Gupta efficiency) [115], [116]. It is not expected that all basins or hydrological regions will demonstrate satisfactory performance from a global parameterization (i.e., one parameter set across all regions or basins) calibration; long-term performance is a more important indicator of accuracy for the bounding curve assessment. Model performance across the entire simulation period should be reported and any basins not meeting satisfactory performance should be investigated further. The presence of regulation on river reaches will impact model performance and reduce the model's ability to adequately match observed flow records during the regulated period. Therefore, only natural, naturalized, or minimally impacted hydrometric gauge records or time periods of unregulated flows should be used for calibration and validation.

Calibration should be automated (e.g., using OSTRICH [117] or other algorithms). The use of multiple metrics to assess model performance, including overall streamflow as well as flow signatures representing peak streamflow, can also be considered for a multi-criteria approach to calibration [118].

3.1.8 Global Climate Model-Driven Model Simulations

The downscaled and bias corrected climate ensemble can force the hydrological model(s) over a continuous historical to future simulation period (i.e., 1987–2100). Each member of the ensemble would generate a single, continuous time series of streamflow. When combined, an envelope of historical and future projected streamflow can be generated that includes the combined effect of multiple sources of uncertainty in the modelling chain.

The time period for historical simulation should be a minimum of 30 years. Subject to the availability of observational data for calibration and verification purposes, it could correspond to a desired and commonly reported IPCC literature reference period of 1981–2010. However, since the historical period defined by CMIP6 models ends in 2016, the baseline reference period could also be chosen to align with 1987–2016.

The future period defined by CMIP6 extends to 2100. Though the guidance for Canada on flood hazard mapping suggests that a climate window of no less than 10 years be used to capture natural climate variability, the literature typically recommends a window between 20 and 30 years [86]. Reference climate windows spanning 30 years and centred on the threshold temperature rise are often used for analyses (see Section 3.1.2).

3.1.9 Flood Frequency Analysis

A historical FFA is a key component for estimating the range of design flood discharges required for bridge design, typically requiring AEPs ranging from 0.2% to 4%. In the suggested approach, the historical FFA relevant to the specific study site would remain the responsibility of the qualified person. Traditional approaches to peak flow estimation under the assumption of a stationary climate would be used, and ideally derived from observed data (see Section 2.1.4). Design floods for future conditions would be reliant on the bounding curves and delta-change factors developed under the initiative (see Section 1.2).

Through the initiative, direct comparison of simulated historical to simulated future flows would be used to derive delta-change factors applicable to the practitioner-derived historical FFA values. The model-to-model comparison of historical to future peak flow values would remove or minimize the effect of model bias and calibration accuracy. Peak flow values over the simulation period can be determined from the ensemble results over climate windows for the historical and future periods for each studied watershed.

3.1.10 Bounding Curve and Delta-Change Factor Development

For each modelled watershed, a time series plot of annual peak flow Q (i.e., annual maxima) over the period 1987–2100 would be developed for each low, medium, and high RCP/SSP, as illustrated in Figure 6. Confidence bands would result from the range of model ensemble results. The time series plots of annual maxima over time, along with their uncertainty bands, represent the bounding curves.

Comparing the baseline annual peak flow (i.e., 1987–2016) against the future condition annual peak flow allows the relative change in peak flow to be estimated. Each peak flow estimate would encompass the climate window time horizon centered on increments of GMT rise. This percent change in annual peak flow derived from the bounding curves represents the delta-change factor.

Bounding curves and delta-change factors would be developed for each studied watershed. The delta-change factors could then be derived directly from the bounding curve for each modelled watershed and by selected GMT rise increments. Conservative delta-change factors could be developed by selecting appropriate confidence levels over the range of outcomes represented by the model ensemble annual maxima results. Selected peak flow estimates for the historical period should be sufficiently low, while selected peak flow estimates for the future period should be sufficiently high to result in larger delta-change factors. To help ensure conservative delta-change factors are produced, a low percentile value, such as the 25th percentile (shown in Figure 6 inset), would be used for the baseline period (i.e., 1987–2016) whereas a high percentile value, such as the 75th percentile, would be used for the future period of interest. In figures 7 and 8, a focus on 2°C GMT rise is used for illustrative purposes.

Selection of the percentile used to represent the distribution is, in part, based on the reliability of the ensemble prediction. By comparing a modelled future to a modelled historical period, the impact of model selection and bias is diminished because it becomes a direct model-to-model scenario comparison, representing only the net change resulting from the climate processes.

The proposed workflow and conceptual methodology for deriving the bounding curves and delta-change factors from the hydrological models is outlined in steps 1 through 6 below and illustrated in figures 6, 7, and 8.

Step 1: Run hydrological simulations for each emission scenario and plot current and future annual maximum peak flow (Q) over time (i.e., 120 years), including confidence bands for each modelled watershed (see Figure 6).

Step 2: Determine GMT rise versus year for each emission scenario using CMIP5 or CMIP6 (see Figure 7). Identify climate windows (e.g., 30 years) centered on increments of GMT rise (e.g., 2°C GMT).

Step 3: Using Figure 6, estimate the percent change in peak flow by comparing the 25th percentile to the 75th percentile peak flow values for the historical and future periods, respectively.

Step 4: Repeat steps 2 and 3 for each 0.5°C increment of GMT rise.

Step 5: Develop delta-change factor plots of GMT rise versus % change in Qpeak (see Figure 8).

Step 6: Repeat above steps for each watershed.

Figure 6: °GMT rise versus year relative to 30-year climate normal periods. Figure is for illustrative purposes only.

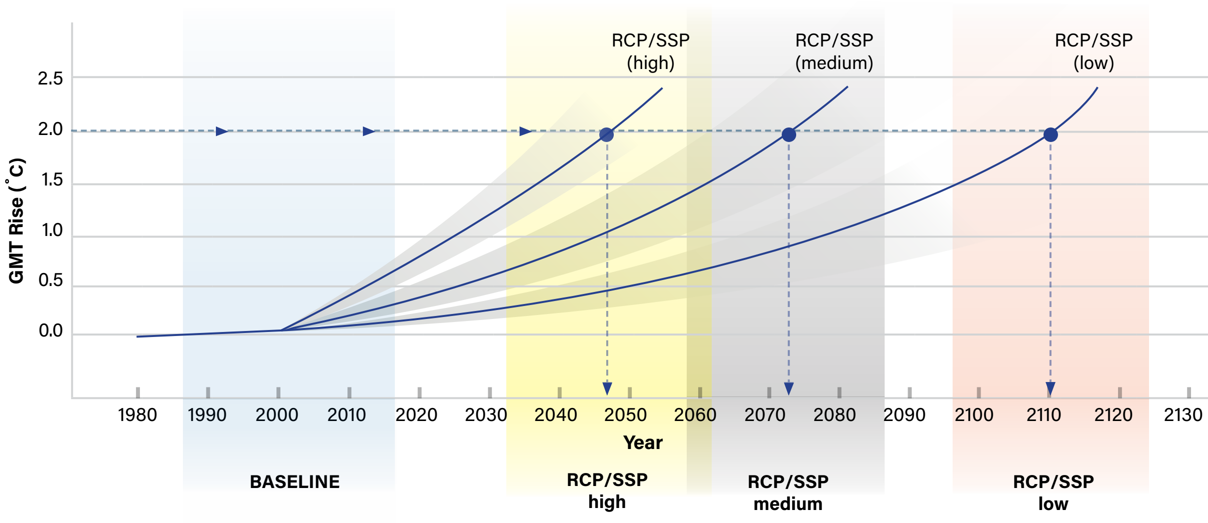


Figure 7: Annual peak flow over time for a specific watershed. Figure is for illustrative purposes only. Hydrological response is representative of a typical snowmelt-dominated watershed in Canada.

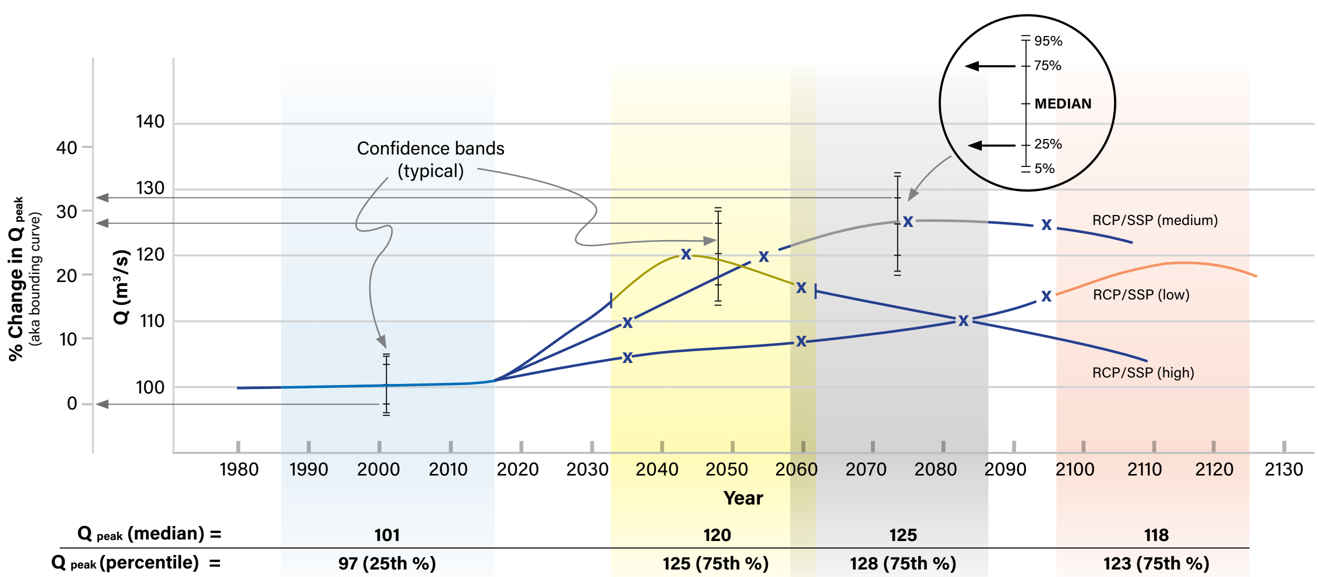
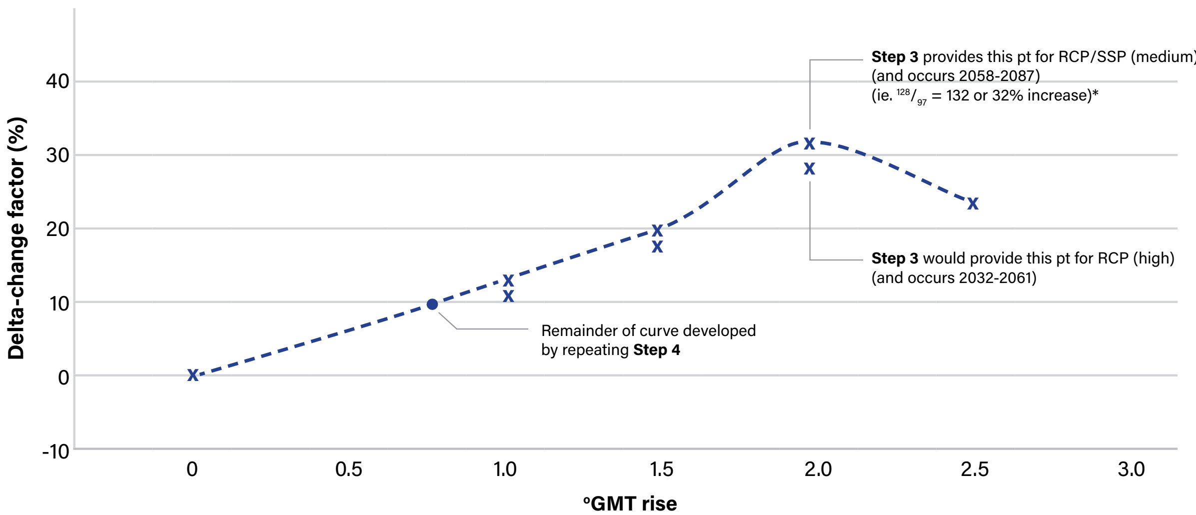


Figure 8: Delta-change factor for a specific watershed excluding uncertainty bands. Figure is for illustrative purposes only.



The bounding curves encapsulate total uncertainty from the modelling chain. Further, by using this modelled current to modelled future comparison, changing flood-generating mechanisms are implicitly captured. For this reason, development of delta-change factors should indicate the season in which the critical future condition flood is expected to occur so practitioners can understand the nature of current and future condition floods.

3.1.11 Applying Bounding Curve and Delta-Change Factors

Equation 2 demonstrates how delta-change factors (ΔQ_T) are derived from the simulated bounding curves, where ΔQ_T represents the percent change in Qpeak for a given a rise in GMT:

$$\Delta Q_T = \frac{Q_{T,\,future} - Q_{T,\,historic}}{Q_{T,\,historic}}\,, \qquad \text{(Equation 2)}$$

where ΔQ_T = percent change in peak flow, $Q_{T,\,historic}$ = peak flow estimate for historical baseline period using 25th percentile, and $Q_{T,\,future}$ = peak flow estimate for future period corresponding to a specific °GMT rise using 75th percentile.

To estimate future condition peak flows using the procedures described herein, a qualified person must first estimate historical peak flows using FFA or other applicable methods. A delta-change factor would be applied to their historical peak flow estimate based on selecting an applicable curve for their point of interest and corresponding increment of GMT rise as described in Equation 3. For example, a 10% difference between the historical and future projected peak flow over the climate window period would result in a factor of 1.1 applied to the historical at-site peak flow estimate.

$$Q^T_{peak,CC} = \left(1 + \frac{\Delta Q_T}{100}\right) \text{ x } Q^T_{peak,historic}\,, \qquad \text{(Equation 3)}$$

where $Q^T_{peak,CC}$ = peak flow estimate for future climate condition corresponding to a specific °GMT rise, ΔQ_T = percent change in peak flow, and $Q^T_{peak,historic}$ = peak flow estimate based on FFA or other applicable methods.

The percent change in peak flow estimates varies with °GMT rise. The worst case scenario (i.e, highest percent change in peak flow) would be evident in the delta-change factors presented in Figure 8. To select a delta-change factor, the governing body would need to specify the °GMT rise from which to select a value.

For example, the governing body could specify that delta-change factors be applied based on the worst case scenario that could occur over the design life of the structure. Although not advisable, a specific °GMT rise threshold could be specified for selection of delta-change factors.

Under some scenarios, predicted future condition peak flows may begin to decrease immediately. In this case, the highest peak flow predictions would occur under current conditions, and it would be appropriate to apply a 0% change to the historical peak flow estimates.

The delta-change factors are expected to be derived from daily time step model output. While the daily peak flow estimates are known to be lower than instantaneous peak flow estimates, the comparative differences between daily and instantaneous historical and future peak flows vary and are unknown. Practitioners will need to consider conversion of daily peak flow estimates to instantaneous values.

Until improved guidance is available, practitioners could apply the appropriate delta-change factors to their instantaneous peak flow assessment on the assumption that I/D ratios would not change in a future climate. Ideally, I/D ratio guidance for future climate will be derived as part of a future initiative or by providing high temporal resolution RCMs to drive representative hydrological models.

3.2 Database Quality Control and Dissemination

Future updates to the CHBDC [1] are anticipated to require that bridges in Canada be designed based on the highest peak flow that could occur over the design life of the bridge [6]. Application of the delta-change factor to historical peak flow estimates derived from traditional methods represents a conservative approach to adjust peak flow estimates to account for climate change. However, the data generated in the initiative need not be limited to these specific quantiles or to bridge and highway design work. These data could be made available or accessible for additional regional applications, such as flood hazard assessments.

Although uncertainty bands are included for the bounding curves, they are not represented in the delta-change factor plots for clarity, consistency in application, and ease of selection. Noting the built-in conservative nature of the delta-change curves, it may be more desirable and cost-effective to conduct a rigorous watershed-specific study that would likely result in a lower peak flow estimate. To aid in this endeavour, the underlying data is expected to be made available to practitioners and researchers as supplemental material, and to support independent peak flow estimates.

To ensure standardization of approach, accessibility of the data, and reproducibility, which are among the recommended best practices for scientific data management [119], it will be important for a responsible organization to invest in deriving the initial bounding curve dataset, to progressively update and publish it and to foster confidence in the data by being transparent. Such organizations could include the affected agencies, such as provincial transportation ministries. Publishing the data in its entirety will enable agencies and practitioners to perform additional quality control checks on the outputs and will offer an additional level of peer review control to the process. At a minimum, the bounding curves and delta-change factors would need to be published and revision-controlled, but ideally, the availability of all model outputs with proper documentation of the workflow would help establish a level of confidence among practitioners and provide a service to the community at large should additional AEP or peak flow quantiles be of interest to the water resources/hydrology practitioner community. By publishing all data generated to produce the bounding curves, practitioners and other agencies could apply their own FFA methods to recreate delta-change factors with confidence using their own proprietary or in-house methods.

Revision control and updating of data in the national dataset will also be required and should be considered as long-term maintenance of design values. Previous values should remain accessible for comparison as climate models and scenarios evolve. This will require consideration of storage capacity by the governing body, as well as ongoing financial and research and development investment in the project.

"Future updates to the CHBDC are anticipated to require that bridges in Canada be designed based on the highest peak flow that could occur over the design life of the bridge."

3.3 Recommended Elements of Approach

Based on the compilation of information from the literature review, the review of research and development activities, and the interviews with experts, the following recommendations are presented to develop a set of bounding curves and delta-change factors across all regions of Canada.

3.3.1 Study Scope

Recommendation 1. Include all hydrological zones across Canada in the initiative, discretized based on considerations of climate and drainage.[2]

> ***Action:*** *Review the delineation of hydrological zones across Canada from existing sources and determine how these would be represented by bounding curves and delta-change factors, paying particular attention to changing peak flow mechanisms. This action may inform hydrological model selection.*

Recommendation 2. Consider hydrological model selection early in the workflow to ensure consistency throughout the modelling chain. Hydrological model selection should consider hydrological zones or regions and their ability to represent physical processes that drive peak flow response.

3.3.2 Climate Ensemble

Recommendation 1. Use the current generation CMIP6 climate scenarios, if possible.

Recommendation 2. Leverage previous work completed for FHIMP (ensemble of CMIP6 GCMs, statistically downscaled and bias corrected for Canada using multivariate approaches), or a SMILE (e.g., CanESM2-LE). This should be decided during the implementation of the initiative based on outputs available from the FHIMP study.

3.3.3 Emission Scenarios

Recommendation 1. Consider low, medium, and high emission scenarios (i.e., RCP 4.5, 6.0, 8.5, or equivalent SSPs) independently to develop bounding curves and to evaluate hydrological response of each watershed over time.

3.3.4 Downscaling and Bias Adjustment

Recommendation 1. Target spatial resolution commensurate with an RCM with the finest practical resolution to align with a minimum hydrological resolution (i.e. 10 x 10 km^2 grid or 100 km^2 sub-basin area).

2 For example, using Statistics Canada's map of Canadian drainage regions: https://www150.statcan.gc.ca/n1/pub/16-201-x/2017000/sec-1/m-c/m-c-1.1-eng.htm

Recommendation 2. Complete statistical downscaling and bias adjustment methods for all of Canada (including transboundary basins), or select an ensemble where this has been done with an appropriate reference dataset.

Recommendation 3. Use daily or sub-daily temporal resolution for the reference and future climate dataset, and for the hydrological modelling time step.

Recommendation 4. Use ERA5 as the bias correction reference dataset, recognizing the numerous reanalyses datasets that are commensurate with ERA5 that could be used reliably for hydrologic model calibration. This affords future bias correction of other meteorological variables should additional hydrological models (e.g., requiring wind and radiation) be included. Consider RDRS and ERA5-Land reanalysis datasets if better suited to selected spatial resolution.

Recommendation 5. As a minimum, bias adjust temperature and precipitation to daily temporal resolution; the suite of bias adjusted climatic variables must consider the needs of the selected hydrologic model(s).

Recommendation 6. Employ multivariate quantile mapping techniques, with preference given to the methods derived by Canon or Papalexiou [40].

3.3.5 Hydrological Model Selection

Recommendation 1. Use the hydrological models and climate ensembles from the FHIMP program [96].

3.3.6 Hydrological Model Setup

Recommendation 1. Apply minimum basin size = 60 km^2.

Recommendation 2. Simulate watersheds with unregulated flows only (i.e., little to no water management interventions) that have sufficiently long and homogeneous hydrometric flow records.

Recommendation 3. Utilize the FHIMP hydrological model setups, which are a combination of gridded and sub-basin models at relatively coarse spatial scales (> 60 km^2) to include hydrological model structural uncertainty within the bounding curves.

> **Note:** Should the FHIMP setups not be ready in time for the initiative, consider establishing a lumped basin model, possibly one with multiple hydrological model structures (e.g., Raven).

3.3.7 Calibrate and Validate Hydrological Models

Recommendation 1. Use the FHIMP model setup and calibrations as they are, given they were completed by expert model developers from across Canada.

> ***Action:*** *Consider investing in a Canada-wide detailed uncertainty and validation study to examine performance across the country and in regions where post-processing corrections may be needed.*

Recommendation 2. Report calibration and validation statistics (i.e., peak flow, Kling–Gupta efficiency, and other performance metrics) for all basins included in the derivation of bounding curves. Identify and improve or remove any outliers that do not meet minimum reliability standards.

> ***Action:*** *For event-based evaluation, include flow signatures targeting peak flow estimation.*

Recommendation 3. Model calibration for the FHIMP models was performed using the SCDNA [49], which is comparable to ERA5 and RDRS reanalyses. Any subsequent model setups should use or be consistent with these products.

3.3.8 Time Horizons for Global Mean Temperature Rise

Recommendation 1. Identify 30-year window time horizons for selected GCM ensembles to reach each increment of GMT rise (see Figure 7) compared against the 1987–2016 baseline period.

3.3.9 Perform Simulations

Recommendation 1. Utilize FHIMP model outputs, which are retrievable from ECCC and other project collaborators. Outputs across a simulation period extending from 1987 to 2100 are desired at a daily time scale.

Recommendation 2. Access an ensemble of GCMs or RCMs with limited membership that has previously been evaluated and downscaled for Canada. Develop a sufficiently large ensemble by selecting multiple GCMs or multiple SMILEs that results in an evaluation dataset of at least 1500 annual peak flow results over a 30-year climate window (e.g., 10 GCMs x 5 initial conditions x 30 years).

Recommendation 3. Center climate windows on increments of GMT rise with emphasis on +2.0°C GMT rise.

Recommendation 4. Include only basins that are minimally impacted by non-stationarity concerns (beyond climate change), thus excluding any regulated basins or basins with significant alteration to land use or land cover.

3.3.10 Derive Bounding Curves

Recommendation 1. Derive bounding curves by running the hydrological model ensemble forced by the complete model ensemble over the 1987–2100 time period.

Recommendation 2. Assess each emission scenario separately to aid in understanding how the peak flow from a watershed is expected to change over time (see Figure 6).

Recommendation 3. Determine the change in peak flow for each increment of GMT rise for each study watershed (ideally), or as an initial step (if computational capacity does not exist to disseminate by subbasin), by hydrological region.

> **Note:** though subbasin scale is the preferred approach for dissemination of the bounding curves and delta-change factors, it is recognized that a significant amount of computational storage, revision control procedures, and a GIS interface will be needed to disseminate results at this resolution to practitioners.

3.3.11 Estimate Delta-Change Factors

Recommendation 1. From the bounding curves, select conservative values (e.g. 75th percentile from a large ensemble, or 95th for a SMILE) for the reference and future periods, respectively, for each increment of GMT rise.

Recommendation 2. For each increment of GMT rise, determine the highest percent change in peak flow. Develop delta-change factor curves that represent percent increase in peak flow from baseline conditions associated with each emission scenario and for each study watershed (see Figure 8).

3.3.12 Applying Delta-Change Factors by Practitioners

Recommendation 1. Make the data used for deriving delta-change factors from bounding curves available to researchers and practitioners.

> **Note:** Confidence bands are not included in the delta-change factor plots to simplify application and to encourage consistency by practitioners. However, uncertainty is explicitly shown until this step in the modelling chain and can be easily determined by examining the relevant bounding curve.

Recommendation 2. AEPs ranging from 0.2% to 4% should be estimated by practitioners in accordance with design flood discharges stipulated in governing codes, including the CHBDC. Practitioners should estimate historical design flood discharge using applicable methods based on the assumption of a stationary climate.

Recommendation 3. Practitioners should apply appropriate delta-change factors to their historical peak flow estimates relevant to the specific hydrological region.

> **Note:** Determining appropriate delta-change factors could use methods such as those applied using regional techniques that consider a range of climatic and physiographic factors, including watershed size, average elevation, slope, aspect, drainage density, and so on. Development of a regional toolkit is beyond the scope of the initiative.

Recommendation 4. In cases where future condition peak flows are expected to immediately drop from the historical reference period conditions, apply a delta-change factor of 1.0 (i.e., current conditions would represent the highest peak flow estimate over the design life of the bridge).

Recommendation 5. I/D adjustment ratios are not included in the scope of this report but should be applied by practitioners as appropriate.

3.3.13 Revision Control

Recommendation 1. Bounding curve analysis and delta-change factors should be updated with each major update to the CHBDC.

3.3.14 Data Control and Dissemination

Recommendation 1. Publish data underpinning the analyses in as much entirety as computationally practical (i.e., model outputs) using accessible and revision-controlled sites to facilitate practitioners and users performing their own analyses.

Recommendation 2. Explore options of who should pay for, maintain, and support revision control of this data.

Recommendation 3: Setup and conduct a feasibility study that tests the adopted methodology from beginning to end for a single GCM/SSP realization, and multiples the time and computational capacity requirements based on the number of ensemble members to be adopted.

3.4 Limitations and Other Considerations

Although this report presents a comprehensive review of best practice in climate change impact assessment for hydrology, and specifically for peak flow assessment, the recommendations in sections 3.3.1 through 3.3.14 represent the first phase of work necessary to derive a national dataset of bounding curves and delta-change factors that will help enable practitioners to conduct peak flow estimates for bridge design that account for climate change impacts. Additional elements could be considered in subsequent iterations or revisions of the database that include, but are not limited to:

- Consideration of anthropogenic changes in Canadian rivers and watersheds (e.g., dams, diversions, withdrawals, and land use and cover changes).
- Consideration of shifting causation of peak flow (i.e., flow generation mechanisms), including shifts in hydrological zone definition (i.e., nival to pluvial).
- Inclusion of multiple hydrological models to better represent various hydrological regions of Canada and to improve reliability of results using different model structures. (i.e., FHIMP ensemble).
- Testing of different or multiple bias adjustment techniques and/or time scales of application of the bias adjustment (e.g., annual, seasonal, monthly, daily) to capture regional variations in climatology and bias offset.
- Development of a tool to aid in delta-change factor selection relevant to the point of interest based on weighted scoring of physiographic factors.
- Completion of a Canada-wide detailed uncertainty and validation study to examine performance across the country, and in regions where post-processing corrections may be needed.
- Estimation of uncertainty and calibration in ungauged basins (where no hydrometric data exist).
- Inclusion of spatial calibration data (e.g., remotely sensed soil moisture or evapotranspiration) or use of flow signatures to improve model calibration performance and the representation of processes driving runoff generation.
- Development of I/D ratios related to future climate and applicable to the use of delta-change factors.
- Model setup and simulated historical and future timeseries data for every sub-basin simulated could be made available through a data portal with a GIS-interface as a service to practitioners for other climate change adaptation studies. This would promote consistency among practitioners and approaches for the water resources community.
- Ensuring long-term storage and maintenance of the database by a responsible authority.
- Updating of bounding curves and delta-change factors with each future release of the CHBDC, next generation CMIP releases, or significant changes to climate science knowledge.

4 Conclusions

Practitioners interviewed for this report unanimously agreed that guidance on predicting peak flows under a future climate, and supporting data to complete these predictions in a simplified manner, are critical for the engineering community. Interviewees also noted that an established Canada-wide standard for incorporating climate change impacts to peak flow

"Practitioners interviewed for this report unanimously agreed that guidance on predicting peak flows under a future climate, and supporting data to complete these predictions in a simplified manner, are critical for the engineering community."

assessments for bridge design would be welcomed by the water resources community. While the intent of the initiative is to simplify peak flow prediction in a manner that ensures conservative bridge design, it is important to value and incorporate the experience, knowledge, and judgement of local practitioners. The initiative should offer tools and data that support and integrate with, rather than replace, existing practice. It is believed that the development of data, guidance documents, and tools to support the water resources community in **applying delta-change factors** will allow conservative peak flow estimation under climate change with reasonable effort. This simplified and standardized approach will promote consistency and resilient bridge design while still encouraging more detailed, and presumably less conservative, peak flow estimates using watershed-specific hydrological modelling approaches.

The focus of this report was to develop a strategy for a **national dataset of bounding curves** from which potential changes in peak flow under a future climate could be derived in the form of delta-change factors. Although the effort would be substantial, it may be feasible to create this dataset at a national scale. The delta-change factors can be estimated from the watershed-specific bounding curves, which can then be applied to historical peak flow estimates from practitioner-derived extreme value analysis. Key components required for developing a national dataset of bounding curves include:

- Selecting a bias corrected and downscaled climate model ensemble for Canada that includes emission scenarios and members.
- Examining a pre-defined delineation of hydrologic basins or zones across Canada to consider unique climatic and hydrological characteristics to aid in hydrological model selection.
- Leveraging existing Canada-wide hydrological model setups for simulated streamflow with a focus on peak flow simulation. This is limited to natural and naturalized flow conditions where observational historical data exists for each hydrological region across Canada.
- Calibrating and verifying hydrological models against observed records and confirming model performance over the historical period by comparing against reanalysis datasets.
- Running hydrological simulations with climate variable forcing extending over the historical and future time horizon (i.e., 1987–2100).
- Determining time frames to reach increments of GMT rise with a focus on 2°C GMT under various emission scenarios.
- Developing bounding curves that plot annual peak flows for historical and future periods for each modelled watershed representing regions across Canada. Bounding curves would include the range of uncertainty over the modelled period.

- Developing delta-change factor plots by selecting conservative values (e.g. 25th and 75th confidence bands) for current and future climate, respectively, and indicating the delta-change factor (i.e., percent change in peak flow) over a range of incremental GMT rise. A key delta-change factor would apply to 2°C GMT rise.
- Advising practitioners to estimate historical peak flows to ascertain design flood discharges ranging from 0.2% to 4% as may be required in future versions of the CHBDC.
- Advising practitioners to apply delta-change factors relevant to the hydrological region and other relevant variables. In recognition of current conditions, delta-change factors would not be lower than 1.0.
- Advising practitioners to consider a variety of hydrologic impacts, including flow regulation, watershed non-stationarity (in addition to climate change), and adjustments to account for instantaneous discharge.
- Conducting a feasibility study using the above outlined approach to ensure viability, computational capacity and practicality issues for generation and dissemination of these data.

Selecting delta-change factors from the figures and data provided under the initiative will remain the responsibility of the practitioner, based on selecting the relevant hydrological region and increment of GMT rise. Furthermore, in selecting the appropriate delta-change factor, practitioners should consider approaches similar to regional FFA that include a variety of physiographic characteristics, such as watershed area, aspect, average elevation, gradient, and drainage density. The selected delta-change factor would be applied to the historical peak flow estimate completed by the practitioner using traditional hydrologic methods while considering any limitations or best practices developed while undertaking the initiative.

Within specific watersheds in various hydrologic regions across Canada, peak flow estimates may trend downwards either immediately or in the future as a result of climate change. This could result in negative delta-change factors that, if applied, would result in new bridges being immediately under-designed for present conditions. For this reason, it will be important to determine when the highest peak flows are expected to occur and their respective values. Ultimately, the selected design flood discharges would be based on the worst case condition, whether that occurs during the current or a future period.

Long-term storage and maintenance of the database will require an ongoing investment by the responsible authority or organization. Accessibility to, reproducibility of, and benchmarking (by revision control of bounding curves and delta-change factors) will be important future considerations required to maintain consistency and usability of the data.

4.1 Benefits to Practitioners and Owners

In a future climate, the temporal and spatial changes to rainfall, snowmelt, and rain-on-snow characteristics could lead to significant changes in peak flow estimates and shifts in flood-generating mechanisms. Therefore, for smaller non-rainfall-dominated watersheds and for larger watersheds, hydrological modelling is required to estimate peak flow. This can be a significant undertaking; the level of effort to build and analyze a climate-driven watershed hydrological model may not be commensurate with the risk imposed on the subject bridge.

The research conducted for this report pursued a data driven approach that sets upper bound, conservative estimates to peak flow estimation that can be applied to frequency analysis using traditional hydrological procedures. Although climate change may cause watersheds to transition to a new paradigm that is not represented in the historical record, a purpose-built database of bounding values can support peak flow estimates under a future climate by applying delta factors to peak flow estimates derived from historical records. In the absence of this tool, owners and water resource professionals would be required to build and calibrate watershed-specific hydrological models and complete a thorough hydrologic assessment over the historical and future period. This type of assessment may be beyond the capacity of industry and may not be commensurate with the scope of a project and its risk profile.

Development of the proposed bounding curves and delta-change factors will allow owners and practitioners to use a simplified approach that relies on traditional hydrologic methods and historical records, albeit at the expense of a more conservative design. It is therefore the owner's prerogative to support the practitioner in completing a more in-depth study, which could typically result in a less conservative design, and consequently, reduced construction and maintenance costs. Investment in the initiative will continue to bridge the gap between scientific knowledge and the application of these principles in practice.

The bounding curves and related delta-change factors are not intended to replace local hydrological expertise but rather to support it. This could be accomplished by:

1. Requiring that qualified personnel use traditional hydrological methods for FFA to derive their own estimates of historical peak flows;
2. Using bounding curves and applying delta-change factors to estimate future condition peak flows; and
3. Encouraging owners and practitioners to complete site-specific climate-informed watershed hydrologic assessments.

The "encouragement" noted in point 3 would be accomplished through the potential savings in bridge construction, operation, and maintenance costs that result from applying less conservative peak flow estimates and through the consideration of hydrologic complexities that can govern design, such as reliance on flow regulation.

This approach allows practitioners the most flexibility in using appropriate site-specific data to derive historical peak flow estimates for design floods, but also applies a consistent Canada-wide standard to adjust those design values to account for climate change. Furthermore, it leverages current best practice in the climate change impact assessment literature without requiring practitioners to undertake extensive research and development work themselves, affording consideration of climate-affected peak flow values within typical budget and scope of work constraints. Finally, this approach maintains practitioner and local knowledge of watersheds and landscapes, including understanding of regional controls and differences in flood generation mechanisms, compounding effects due to the dynamics of weather, antecedent conditions, dynamically contributing areas, and flow routing, by leaving the estimation of design peak flows in the hands of local practitioners and agencies.

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