Flood Frequency Analysis and Dam Safety

IN THE 21ST CENTURY CLIMATE

OURANOS

CREDITS

Project coordination:

Anne Frigon (Ouranos), Kristina Koenig (Manitoba Hydro).

Collaborators on the Blueprint Flood Frequency Analysis (Working Group 1):

Jacinthe Clavet-Gaumont (Ouranos, now at Hydro-Québec), David Huard (Ouranos), Jean-Luc Martel (Lasalle-NHC, now at ETS), Jonathan Jalbert (Polytechnique Montréal), Isabelle Demers (UQAM), David Godin (MELCC), Sébastien Langlois (Hydro-Québec), Matthew MacDonald (Ontario Power Generation), Alec Mercier (RT), Getnet Muluye (Manitoba Hydro), John Perdikaris (Ontario Power Generation), Elaine Robichaud (Hydro-Québec), Gabriel Rondeau-Genesse (Ouranos), Kevin Sagan (Manitoba Hydro), Phil Slota (Manitoba Hydro), Nathalie Thiémonge (Hydro-Québec), Yibing Zhang (OPG).

Collaborators on the Uncertainty-Aware Flood Frequency Analysis (Working Group 2):

David Huard (Ouranos), Kevin Sagan (Manitoba Hydro), Biljana Music (Ouranos), Marco Braun (Ouranos) Elyse Fournier (Ouranos), Alexis Hannart (Ouranos, now at Axionable), Elmira Hassanzadeh (Polytechnique Montréal), Jonathan Jalbert (Polytechnique Montréal), Simon Lachance-Cloutier (MELCC), Sébastien Langlois (Hydro-Québec), Marco Latraverse (Rio Tinto), Matthew MacDonald (Ontario Power Generation), Alain Mailhot (INRS-ETE), John Perdikaris (Ontario Power Generation), Luc Perreault (Institut de recherche d'Hydro-Québec), Phil Slota (Manitoba Hydro), Nathalie Thiémonge (Hydro-Québec), Richard Turcotte (MELCC).

Collaborators on the Adaptation Options (Working Group 3):

Phil Slota (Manitoba Hydro), Charles Poirier (MELCC), Kurt Kornelsen (Ontario Power Generation), Nathalie Thiémonge (Hydro-Québec), Elaine Robichaud Hydro-Québec), Alec Mercier (Rio Tinto).

Authors:

David Huard (Ouranos), Jacinthe Clavet-Gaumont (Ouranos, now at Hydro-Québec), Phil Slota (Manitoba Hydro), Kurt Kornelsen (Ontario Power Generation), Charles Poirier (MELCC).

Advisory Committee:

Leslie Dolcine (Hydro-Québec), David Godin (MELCC), Fanny Houdré (Hydro-Québec), Kurt Kornelsen (OPG), Sébastien Langlois (Hydro-Québec), Bruno Larouche (Rio Tinto), Jarrod Malenchak (Manitoba Hydro/Canadian Dam Association), Jean-Luc Martel (Lasalle-NHC, now at ETS), Marie-Claude Simard (Hydro-Québec).

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PARTICIPATING INSTITUTIONS

Hydro-Québec

Québec's publicly-owned electric utility, Hydro-Québec is North America's largest hydroelectric producer, generating 99% of its electricity from renewables over the Quebec territory.

Manitoba Hydro

Manitoba Hydro, the province's public electric and natural-gas utility, produces approximately 98% percent of its electricity through hydropower.

Ministère de l'Environnement et de la Lutte contre les changements climatiques du Québec (MELCC)

The MELCC monitors dam-operator compliance with the *Dam Safety Act* and securely operates 820 dams on behalf of the provincial government, working closely with other stakeholders to manage Québec's water regime based on safety, fairness and sustainable-development criteria. Other responsibilities include the maintenance and operation of the province's hydrometric network, operational flood forecasting and the production of hydroclimatic scenarios.

Ontario Power Generation (OPG)

An Ontario crown corporation, OPG produces more than half of all electricity used in the province, mainly from hydro and nuclear stations.

Ouranos

Located in Montréal, the Ouranos consortium conducts and funds research on regional climatology, climate change impacts and adaptation options.

Rio Tinto

The aluminum-product group of Rio Tinto is one of the world's largest producers of bauxite, alumina and aluminum, and owns hydroelectric facilities in Québec and British Columbia that power its smelting operations.

TABLE OF CONTENTS

INTRODUCTION

In Canada, the provinces regulate dam safety with legislation that references standards inspired by or mirroring the Canadian Dam Association's *Dam Safety Guidelines*. Among the many design criteria and inspection requirements included in the Guidelines, every dam must be able to accommodate extreme flood events; how extreme depends on the magnitude of damages should the infrastructure fail. Dams posing the greatest hazards are designed to sustain the probable maximum flood (PMF): "the largest reasonably plausible flood that could occur at some location and at some time of the year, based on meteorological and hydrological considerations" (WMO, 2009). Dams in this extreme category include major generating stations on the lower Nelson, La Grande, Columbia and Saint John rivers, among others. Dams in lesser-hazard categories are designed to sustain extreme frequential floods, defined as flow values exceeded only once every 1,000 or 10,000 years.

To estimate frequential floods, the standard engineering practice consists of selecting and fitting a statistical distribution to observed river flows, and computing the percentiles corresponding to the design frequency. This short description hides the myriad difficulties that professional engineers face in practice, including applying the method to ungauged watersheds, short-time observational series, missing data, measurement errors and changing climate conditions. Indeed, both recent historical observations and climate change simulations show trends of more frequent and intense extreme precipitation events in many regions of Canada. Some regions are also expected to experience shorter winters and less snow accumulation, which could reduce spring floods. Thus, climate change adds a layer of complexity to dam-safety evaluation, as engineers are increasingly asked to demonstrate that infrastructures are climate-proof.

The question is no longer whether to factor climate change into dam safety, but rather how to do it. Several renowned organizations, such as the International Hydropower Association (IHA), the International Commission on Large Dams (ICOLD, with its technical committee on climate change) and UNESCO (with the Climate Risk Informed Decision Analysis (CRIDA)) have considered the issue and developed guidelines that incorporate climate change into the decision process (ICOLD, 2016; IHA, 2019; UNESCO, 2018). ISO recently published a standard on adaptation to climate change that provides principles, requirements and guidelines (BSI Standards Publication, 2019). Also relevant for dam managers are the guidelines developed by Ouranos (Fournier et al., 2020), which propose methodologies to integrate climate change into energy production and asset valuation. Certainly, climate change affects hydrology, but it is still difficult to accurately predict how it will impact flood events.

Accounting for climate change in the computation of dam safety criteria is challenging, in part because hydrological projections are the end point of a cascade of models and hypotheses whose individual uncertainties compound. A previous project estimated future probable maximum floods by using weather information from climate model simulations, rather than from the standard observed weather patterns (Ouranos, 2015). The present project is a second phase of this work and focuses on the climate change's influence on extreme frequential floods.

Currently, no consensus exists on how to account for climate change in flood regulations. Despite considerable scientific literature on the impacts of climate change on flooding, gaps still remain on how to translate the evolving science into mainstream engineering practices and dam safety assessments.

To promote progress on the issue, Ouranos convened working groups comprised of dam owners, regulators, engineering firms, climate scientists, professional associations, and academic researchers in hydrology, climate and statistics. This collaboration aims to propose a pragmatic methodology that incorporates future climate projections into the estimation of 1,000 and 10,000-year flows used for dam-safety assessments. The insights from this exercise then fed reflections on appropriate adaptation options.

After a brief refresher on flood frequency analysis, the report introduces the project's underlying philosophy and the structure of the collaboration with experts (Project Description). Proposed Methodologies are then presented, followed by results across Canada. This sets the stage for a discussion of Adaptation Options and concluding thoughts. Our hope with this work is to inspire discussions about both the science of frequency analysis in light of climate change, and its application to engineering practices in operational contexts.

FLOOD FREQUENCY ANALYSIS EXPLAINED

Flood frequency analysis consists of estimating how frequently, on average, thresholds are exceeded. Thresholds can be expressed as peak flow or flood volume, but the objective is ultimately to associate flow values with probabilities of occurrence. For example, there is a one-percent chance that a particular peak flow would be exceeded in a given year. This would be relatively easy to determine if watersheds did not change over time and we had access to thousands of years of flow observations. In this case, we could rank flows and compute their percentile: the 99th percentile of annual maxima is, by definition, the value exceeded an average of once every 100 years. To be clear, 100-year events could occur two years in a row, but the average interval between events is 100 years.

In practice however, flow records in North America rarely extend beyond 100 years, and using this ranking method to estimate 1,000 and 10,000-year floods would simply not work[1]. To work around this, flood frequency analyses make hypotheses about the relationship between the magnitude of annual flow maxima and their likelihood. These hypotheses are encoded by a parametric probabilistic model, typically a statistical distribution, whose parameters are fitted to observations. That is, we assume that annual maxima are sampled from a statistical distribution, estimate the distribution's parameters from the observation record, then use the same parameters to compute whichever percentile we are interested in. Figure 1 is a conceptual illustration describing this process, where flow maxima are identified over blocks of values (usually one year), then used to fit a distribution.

Although this approach allows extrapolation to very rare events, the estimates' accuracy depends on the choice of distribution and its parameters. In practice, different distributions are tested and the one with the best fit is chosen. This practice, however, clashes with statistical theory, which suggests that only distributions from the family of extreme value distributions should be used to extrapolate to rare events. Indeed, these distributions are the only ones whose shapes reflect the fact that they describe a series of maxima, and can justify extrapolating events outside of the historical record[2]. As for distribution parameters, they strongly depend on the data record's

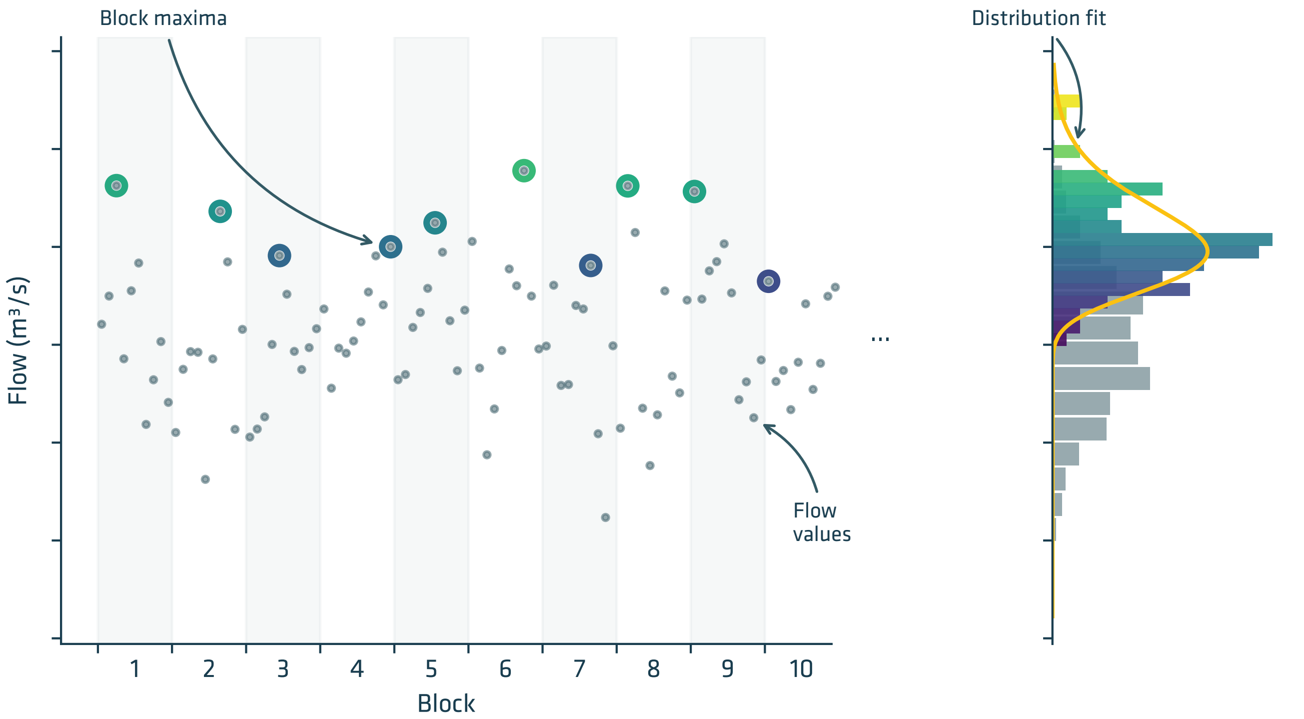

Figure 1: *The maximum flow value within each block is identified (left) and the series of maxima is fitted to an extreme value distribution (right). In practice, blocks are usually defined as periods of one year.*

1 Note that we do not use the terminology return period, because it lacks clarity in non-stationary context. A 1:10,000 event is an event that in a given year has one chance over 10,000 to be exceeded.

2 When extrapolating extreme events whose magnitude goes beyond observations, extreme value distributions are the only probability distributions supported by a formal theory and rigorous mathematical arguments (Coles, 2001).

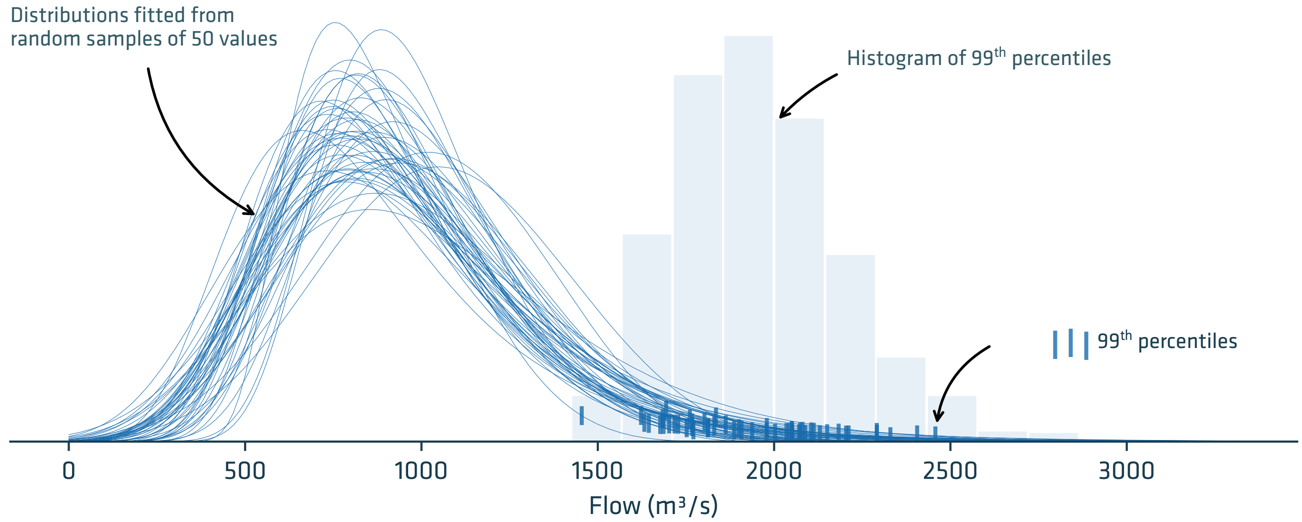

Figure 2: *Effect of sampling uncertainty on parameter estimation and percentile estimates. Random samples of 50 values from one extreme value distribution are generated, from which parameters are estimated and then the 99th percentile calculated.*

quality and size. In practice, short records and measurement errors introduce large uncertainties in frequency analysis, especially when estimating the magnitude of rare events. The conceptual Figure 2 shows just how much variation is likely when estimating the 99th percentile from a record of 50 values sampled from an extreme value distribution. In this simple example, the 99th percentile estimate suffers from ±25% errors, only due to parameter uncertainty. This underlines the challenge of identifying climate change signals among such noise.

Short records are not the only issue affecting flood frequency estimates. If dams, diversions, land-use, erosion or climate cycles have affected flow, then we cannot assume that a single statistic distribution describes an entire record. For example, a step change in flow caused by a diversion could be described by two distributions: one before the change and one after. To describe slow, gradual changes, a practical solution is to assume that the distribution parameters vary continuously as a function of time. Defining these functions, however, requires additional parameters, whose estimation will again depend on short data records.

Different strategies exist to compensate for short records. One is to examine sedimentary layers for evidence for past floods. For example, pollen found in sediment cores from Saanich Inlet, Vancouver Island, point to a flood in the Fraser Valley 11,000 years ago (Blais-Stevens, Clague, Mathewes, Hebda, & Bornhold, 2003). Although relevant, this type of information is difficult to incorporate into risk analysis and design flood values (DFV). Another strategy consists of gathering data from nearby watersheds with similar climatic and hydrological characteristics. Called regional frequency analysis, this approach assumes that multiple watersheds share some parameters of statistical distributions. Instead of extending data records over time, regional frequency analysis extends records over space.

Yet another strategy to acquire more data is to use climate models and hydrological models to generate synthetic flow series. Climate models are planetary climate simulators that simulate hundreds of variables: temperature, pressure, winds, humidity, rain and snow, currents, soil moisture, etc. When compared to real-world observations, climate models perform relatively well for some variables, such as surface air temperature, and poorly for others, such as the many variables related to cloud formation. Among the poorly simulated variables are surface and subsurface runoff, in part due to models' coarse spatial resolution. Hydrologists thus turn to hydrological models, carefully calibrated to a given watershed, to convert time series of precipitation, temperature, solar radiation, etc. simulated by climate models, into flow series.

A number of conditions must be met to produce realistic hydrological simulations. For one, the mean values of simulated weather variables must be comparable to observations across seasons. Discrepancies of just a few degrees will have an important influence on evapotranspiration and snow accumulation, affecting the realism of summer droughts and spring floods. For precipitation, it is also important that not only the means are well represented, but also the tail end of intense rainfalls, which control summer and fall floods. Climate model simulations typically do not meet all these criteria, and post-processing algorithms, downscaling to local scales and/or performing bias correction, are usually applied to climate model variables to better match observations. These post-processing algorithms essentially transform simulated distributions, such that over the historical period, they match observed distributions.

Figure 3: *Hydroclimatic modeling pipeline. GHGA emissions scenarios define the evolution of GHG gases and aerosols in the atmosphere over the next century, which influence weather and climate conditions simulated by climate models. Climate model simulations yield time series of variables such as temperature and precipitation, which are post-processed to better match observations' statistics over the recent past. These corrected time series then drive an hydrological model, previously calibrated to a given watershed using observed time series of weather and flows.*

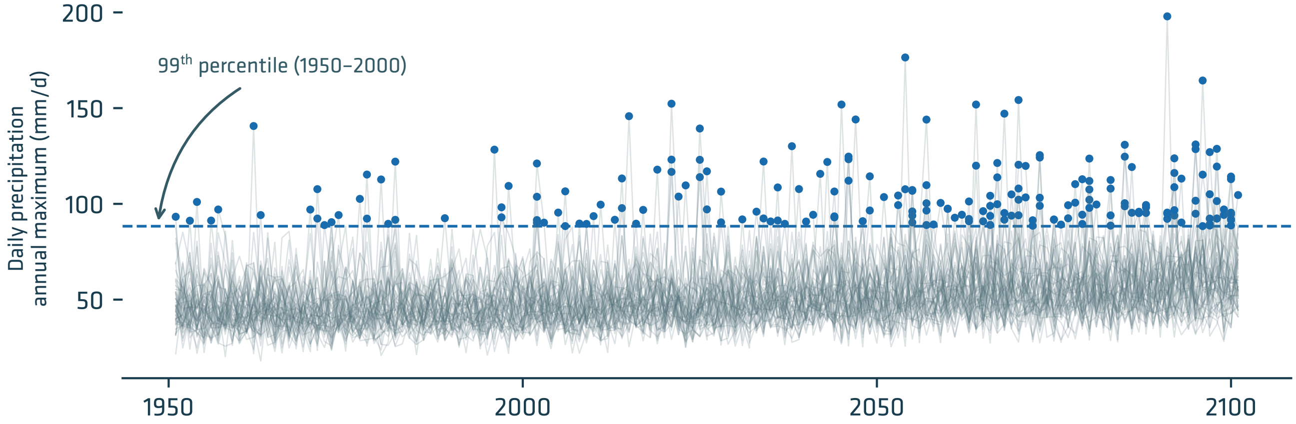

Figure 4: *Annual maxima of daily precipitation over the Toronto region as simulated by the CanESM2 climate model large ensemble experiment under the RCP 8.5 emissions scenario. Each line represents the series of annual maxima simulated by one of the 50 members of the ensemble. The horizontal dashed line indicates the 99th percentile, i.e. the value exceeded on overage 1% of the time over the 1950–2000 period. By the end of the century, the model projects a five-fold increase in the number of events (blue dots) exceeding this threshold.*

Because the dynamics of weather are so chaotic, each individual climate simulation is unique. That is, while simulations share long-term climate properties, their day-to-day patterns are independent from one another. This makes it possible to run dozens of simulations covering a given period (e.g. 1950–2020) to explore rare, extreme events that may not have happened over the actual historical record. For example, the observed record could include a few very snowy winters, but no combination of a snowy winter, quick onset of warm spring temperatures and heavy rains, leading to an intense spring freshet. Analyzing the frequency of extreme events in climate simulations can be seen as a physical approach to flood frequency analysis.

This physical approach is especially valuable when considering the future. Rising concentrations of greenhouse gases and aerosols (GHGA) change earth's radiation balance, elevate surface temperatures and modify the hydrological cycle. Running climate model simulations with an array of future GHG scenarios enables us to appreciate the spread of possible climate conditions in 2050 or 2100. Again, by running a cascade of climate models and hydrological models, it's possible to estimate how climate change could impact the frequency of extreme flood events. Some regions might see decreases in peak spring floods due to a reduced snowpack, while others might see increases due to more intense rainfall events. Analyzing how models react to GHGAs is currently the best way to understand how flood risk might evolve in a changing climate. As an example, Figure 4 presents a time series of annual maximum daily precipitation around Toronto from 50 different climate simulations of the Canadian climate model CanESM2 under GHGA emissions scenario RCP 8.5. It shows a clear influence of GHGA on precipitation intensity.

In practice, using climate model projections to assess current and future flood risks is fraught with difficulties. One challenge is that climate models do not always agree with each other, especially at small local scales. While strong consensus exists that GHGA influences radiation and surface temperatures, its effects on clouds and precipitation varies significantly from one model to another. Different hydrological models will also respond differently to the same precipitation and temperature time series. High percentiles estimated from flow time series are highly dependent on the statistical distribution, and sometimes on the method used to estimate parameters. At each step, scientists have various options and it's often unclear which one is best, or even if a best option exists. This report strives to make sense of the options offered by science and to propose pragmatic methods for operational contexts, where time and resources are limited.

PROJECT DESCRIPTION

The sheer number of methodological choices that can influence the outcome of future climate frequency analysis can be daunting. Indeed, for each choice (GHGA scenario, climate model, post-processing method, hydrological model and its calibration method, etc.), there are two typical pathways: choose one option or perform a sensitivity analysis on multiple options. Choosing a single option requires consensus, which in turn might entail discussions on decision criteria, as well as performing preliminary analyses to rank options. As discussed in Kalra et al. (2014), this “agree-on-assumptions” approach is vulnerable to gridlock and biases. When no consensus can be found, the second option is to consider a list of options and perform a sensitivity analysis. While this enables the study to move forward, it also multiplies the number of results to analyze and discuss, eventually slowing progress.

To simplify the decision-making process, the project was divided in three sets of tasks, with a working group assigned to each. Working Group 1 (WG1) would design a flood frequency method that met three objectives:

- cater to risk-averse decision-makers
- be easily applicable to watersheds across Canada,
- require little or no expertise in climate science

Working Group 2 (WG2) would develop a methodology that took into account as many uncertainties as possible. Faced with a methodological choice, WG1 would pick the option leading to the greatest DFV (design flood value), while WG2 would seek to consider all WG1 options and their respective likelihood. Meanwhile, Working Group 3 (WG3) would focus on how best to adapt existing infrastructure to an evolving risk environment.

The WGs were comprised of: dam managers, engineers and hydrologists from Manitoba Hydro, Ontario Power Generation, Hydro-Québec, Rio Tinto, and the Québec Ministry of the Environment and the Fight Against Climate Change (MELCC); academic researchers in hydrology, statistics and climate science from three universities; and Ouranos staff specialized in climate scenarios for the hydro-power sector. An Advisory Committee oversaw the progress of all three working groups, adjusting timelines and deadlines to accommodate the busy schedules of dam managers during spring (flood freshet) and academic researchers during fall (grant applications).

WG1 was predominantly comprised of practitioners from government and utilities, while WG2 attracted a larger proportion of university researchers. During the first year, both groups met monthly for one hour via teleconference, usually gathering 9 to 15 participants. Working Group leaders would review progress since the last meeting, discuss obstacles and present options for next steps. Participants debated recommendations to move forward, shared internal reports and suggested scientific publications proposing solutions. At regular intervals, technical reports synthesising work were submitted to participants and the Advisory Committee for feedback.

Both methodologies proposed in this report were designed and tested on a handful of watersheds selected by participants. This selection ensured that participants were familiar with existing infrastructure, as well as the watersheds’ hydrology and climate, and could provide relevant data and reports to feed into the methodologies. And since flood frequency studies based on observed data were available for all selected watersheds, findings could be readily compared and the methodologies evaluated.

During the second year, the methodologies from both WG1 and WG2 were applied to these selected watersheds and results compared. The comparison showed that WG1’s methodology did not always yield results larger than WG2’s estimates. WG1’s methodology was thus modified to return values closer to the upper end of WG2’s uncertainty envelope. WG3 was comprised of dam managers from the private sector, public utilities and government agencies. While WG1 and WG2 developed methodologies and generated results, WG3 reviewed published climate change adaptation guidance and formulated a methodology to develop adaptation strategies for their sites of interest. WG3 teleconference meetings were held to discuss and review the developed methodology. After receiving the preliminary results from WG1 and WG2, WG3 members generated proposed adaptation strategies, which were presented and discussed during a one-day in-person workshop.

During year three, WG1’s modified methodology was applied to a larger set of watersheds across Canada. This reality check helped identify remaining weaknesses and potential roadblocks to wider, more general use. The final product, after being reviewed by project participants, was then posted to a public server, allowing users to import project findings into geographic information systems as map layers. Although these map layers do not replace in-depth at-site studies, they may serve as a useful starting point for developing adaptation strategies in the face of changing hydroclimatic conditions.

PROPOSED METHODOLOGIES

This section primarily focuses on WG1's methodology, as it is simpler and more easily replicable than WG2's and is used to create the pan-Canadian results. Due to the complexity of WG2's methodology, this report presents only a general outline.

Blueprint Flood Frequency Analysis – WG1 Methodology

WG1's method aimed to be simple enough for practicing engineers using easily available datasets, yet able to generate results more conservative than those obtained with WG2's best-estimate approach. To ensure that the method remains credible and robust enough for regulators and reasonably familiar to practitioners, it was based on current literature and dam owner practices. Members of WG1 and the Advisory Committee defined the approach and consulted throughout the process. The methodology was developed initially on five watersheds of interest (Figure 5), with the main goal of producing climate-change maps of 1,000 – and 10,000-year floods across Canada.

Figure 5: *The five watersheds used to develop the methodology.*

The many objectives both shaped the development process and constrained methodological decisions. We began with the naive idea to use direct outputs from climate simulations to estimate extreme floods, as we thought that such an approach would make it relatively easy to cover all Canadian watersheds. WG1 members considered it unacceptable to use runoff simulated by climate models because it poorly matched observed runoff. A second option, exploring flow proxies based on precipitation, proved unworkable because the studied watersheds are largely influenced by snowmelt. There seemed to be no way around using hydrological models to simulate flow.

Hydrological modeling implies having a good set of observed flows to perform an adequate calibration and validation of the hydrological model for each watershed. This was not an issue for the five chosen watersheds, because the data were readily available, but replication elsewhere would certainly be more challenging. To respect the project timeline, we searched for existing datasets that would enable us to access hydrological simulations for a large number of Canadian watersheds. Work by Martel et al. (2021) seemed to satisfy the concerns of WG1 members. The work calibrated a hydrological model for more than 700 watersheds based on observed natural flow from HYSETS dataset (Arsenault et al., 2020). It used GR4J, a parsimonious hydrological model (Perrin, Michel, & Andréassian, 2003) coupled with the CemaNeige snowmelt module (Valery, 2010), a combination that academic researchers had had good experiences with. The choice of a single simple lumped model for the entire study is not ideal, but was justified by the project's time and resource constraints. In an operational setting, hydrologists would rather use a more elaborate model carefully calibrated to reproduce flows on sub-watersheds and accounting for reservoir routing[3].

3 In a textbook application, each model would be run with different sets of equally plausible parameters. Additionally, different models could be used to create a multi-parameter multi-model ensemble, and assess model-related uncertainties. We expect extreme flows to be sensitive to these choices.

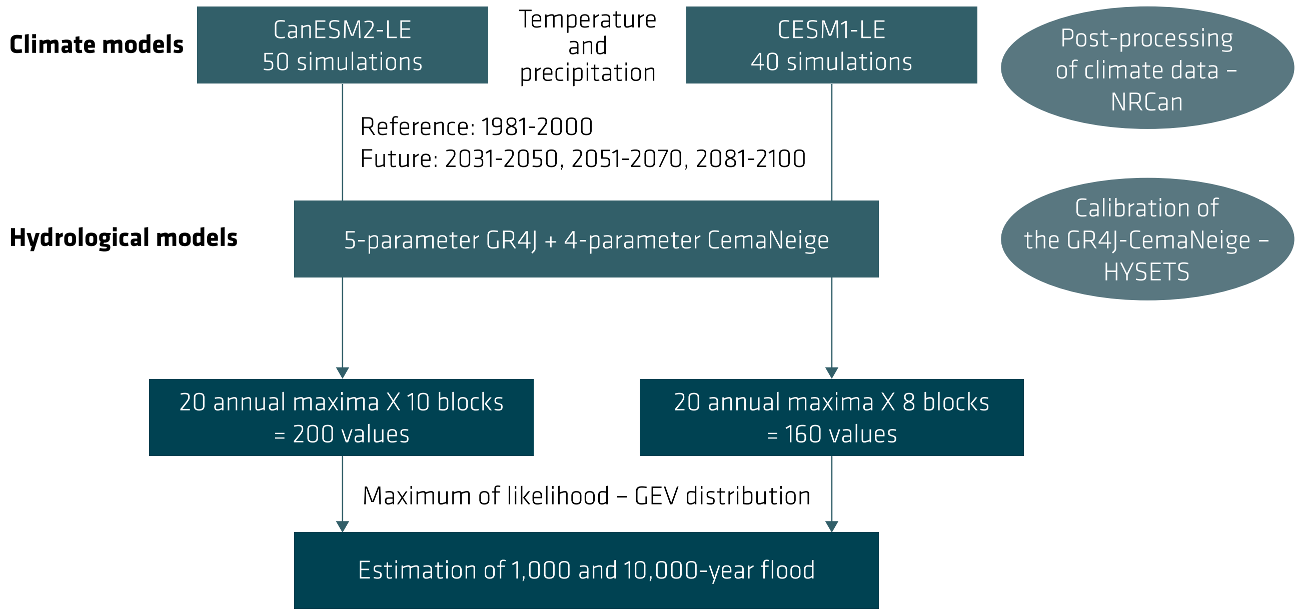

Figure 6: *Approach developed by WG1 inspired by Martel et al. (2021).*

The climate change aspect of the project would be covered by GR4J+CemaNeige simulations driven by daily precipitation and temperature output time series from two Global Climate Models (GCM): CanESM2 (Canadian Earth System Model version 2) and CESM1 (Community Earth System Model version 1). Each of these models had conducted large ensemble (LE) experiments, that is, a large number of climate model simulations (called ensemble members) initiated with slightly different initial conditions and designed to assess natural climate variability. For CanESM2, 50 members were available (Fyfe et al., 2017), while CESM1 counts 40 members (Kay et al., 2015). Both ensembles span the years until 2100 and simulate climate under the future greenhouse gases and aerosols (GHGA) concentration scenario RCP 8.5 (Meinshausen et al., 2011). Representative Concentration Pathway 8.5 is the pathway tracking observed emissions over 2005–2020 most closely, and is likely to do so until 2030 (Schwalm, Glendon, & Duffy, 2020). Around 2050, the "Stated policies" emissions scenario from the International Energy Agency lays roughly halfway between RCP 4.5 and RCP 8.5. Some consider RCP 8.5's projected emissions beyond 2050 to be less likely, as they are based on a five-fold increase in coal use, which is thought to have peaked in 2013 (Hausfather & Peters, 2020). Despite this, RCP 8.5 can be considered a useful scenario to explore the upper range of the climate change response[4].

Before being fed into the GR4J+CemaNeige hydrological model, data from both climate model ensembles (daily precipitation and temperature series) were first post-processed using the so-called quantile mapping approach (Chen, Brissette, Chaumont, & Braun, 2013). The reference dataset used for post-processing is Natural Resources Canada's (NRCan) gridded daily dataset (Hutchinson et al., 2009). The resulting simulated annual maxima (AM) flow values were then extracted over four 20-year periods: 1981–2000, 2031–2050, 2051–2070 and 2081–2100. Each 20-year period counts 1,000 (20 × 50) simulated AM from CanESM2-LE and 800 (20 × 40) from CESM1-LE.

Our selection of climate models can be legitimately criticized. Indeed, current best-practices in climate impact studies recommend using enough climate models to cover a wide range of plausible climate responses to GHGA. Aggregating results from many different models also reduces the influence of individual model errors, leading to more robust results. Impact studies typically count a few dozen different models drawn from the Coupled Model Intercomparison Project (CMIP). Using only two models is a significant deviation from the norm, and the rationale for this trade-off has to do with the properties of extreme values and the need for long records of annual maxima.

To better illustrate this trade-off, we compared the climate change anomalies for precipitation and temperature of the two large ensembles against CMIP5 simulations (Taylor, Stouffer, & Meehl, 2012). Until 2050, both large ensembles show large changes in temperature and they cover a large range of changes in precipitation. With the aim of being conservative, it is reassuring to know that the two models used are among those showing the

4 Note also that GHGA concentration scenarios, not emissions scenarios, typically drive climate models. The concentrations in RCP 8.5 are at the low end of concentrations compatible with the RCP 8.5 emissions (Booth et al., 2012).

largest changes in temperature and consequently the highest impact that temperature rise may have on floods. After 2050, the two large ensembles are no longer the most conservative choices; other climate models simulate higher temperature increases.

On the other hand, our large ensembles do not consider the possibility of a less-warm future (represented by RCP 4.5 simulations). Somewhat counter-intuitively, these projections might lead to the highest risks of floods. Indeed, for moderate levels of warming, increased moisture from the ocean can sometimes compensate for shorter cold seasons, and lead to increases of both snow depth and flood risks in northern regions (Gaur, Gaur, & Simonovic, 2018).

As discussed earlier, flood frequency analysis extrapolates rare flood events based on a statistical distribution fitted to an observational record. WG1 members achieved this using various methodologies. Some used mechanisms to select the best-fit distribution, while others imposed a pre-set distribution based on established institutional practices. A consensus proved difficult to achieve, and agreement was finally found by going back to theoretical considerations. Indeed, the generalized extreme value (GEV) is the only suitable statistical distribution that extrapolates maxima to high yet unobserved percentiles (Coles, 2001). So although hydrologists almost never use this distribution in practice, the theoretical argument and the need for a unique distribution applicable across Canada led us to select the GEV. Further supporting this decision, Zhang, Stadnyk, & Burn (2020) putting Canadian lives and property at risk. Projected variations in precipitation and temperature are expected to further intensify extreme events, necessitating improved flood planning and water resource management. The Natural Sciences and Engineering Research Council funded FloodNet project is developing a standardized flood estimation manual for Canada; such a nation-wide manual would make flood frequency application more effective, consistent, and reproducible, reducing the need for subjective judgement. This research investigates a preferred at-site flood frequency distribution for Canadian annual peak flow dataset. Four frequently used distributions: Generalized Logistic distribution, Generalized Extreme Value distribution, and Pearson Type III distributions with and without log transformation, are assessed using two robust goodness-of-fit tests (i.e., Modified Anderson-Darling test and L-Moment ZDIST test found the GEV distribution was better than other considered distributions (Generalized Logistic, Pearson Type III, Log Pearson Type III) for the purposes of a preferred statistical distribution for at-site flood frequency in Canada. The study found that the GEV was not only accepted for the largest number of Canadian peak flow series, but also had the best predictive performance for estimating the 1 in 25-year flood percentiles in terms of both predictive bias and uncertainty.

The choice of a unique distribution for all watersheds, however, raised a thorny issue. For some watersheds, we noticed that the GEV gave a poor fit to the data and the bias in estimated percentiles was large enough to be unacceptable to participants. Our explanation for this goes back to the properties of the GEV, which is the limit distribution for the maxima of a sequence of independent and identically distributed random variables. For many Canadian watersheds, the annual maximum flow occurs once a year, during the spring snow melt. We could argue that because there is only one snow melt event per year, there is no sequence from which to pick a maximum, and thus the conditions of applicability of the GEV are not met.

Our solution to this is to take the maxima over multiple years. That is, instead of computing maxima over a single year, we compute maxima over a five-year sequence. The fitted distribution therefore represents a distribution of multi-annual maxima and a transformation is performed for parameters to describe the likelihood of annual maxima. In other words, even though the actual distribution of annual flow maxima might follow a Log Pearson III distribution, by taking multi-annual maxima, it's possible to use a GEV to approximate the tail end of the distribution correctly and extrapolate to large, unobserved percentiles (see Figure 7).

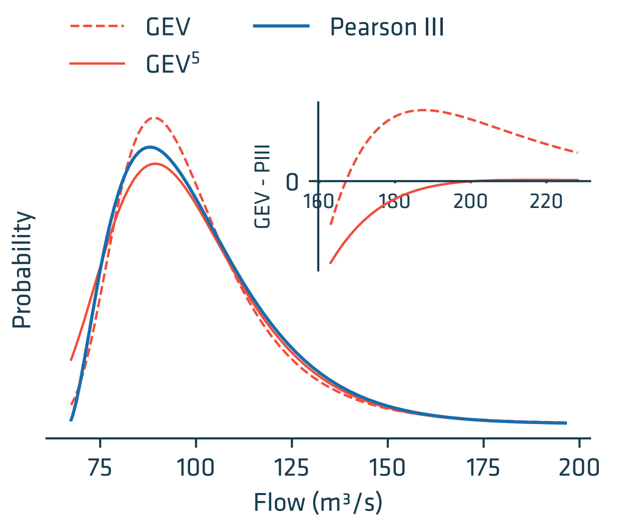

Figure 7: *Although the GEV might not reflect the distribution of annual flows, it can capture the shape of extreme values in the upper tail. In this example, a sample of 5,000 values drawn for the Pearson III distribution is fitted by a GEV and by a GEV^5 (maxima of blocks of 5 values, followed by a transformation of variable). Neither the GEV or GEV^5 match the mode of the distribution, but the difference between the Pearson III and the GEV5 is close to zero for large percentiles (inset).*

Of course, using longer sequences results in smaller samples of maxima and small samples lead to parameter uncertainty. This is where large ensembles prove so useful. Instead of extracting maxima over multiple years, we can extract maxima over multiple ensemble members and still end up with a reasonable sample size.

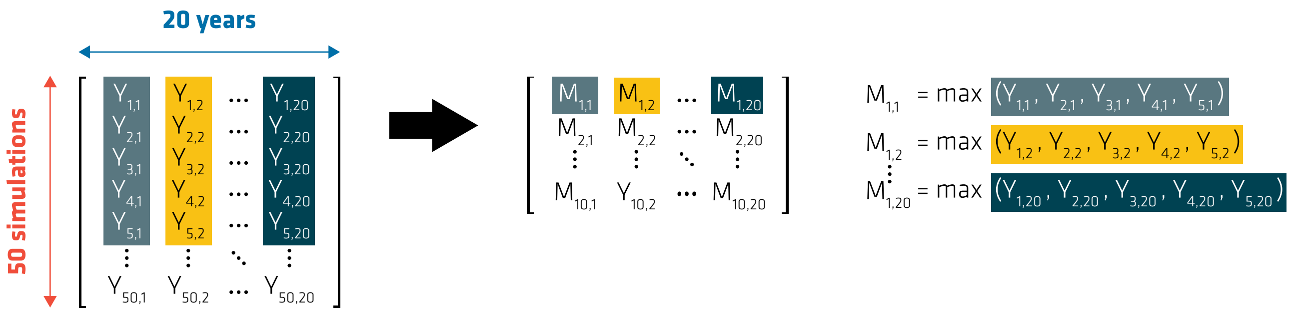

Figure 8: *Description of the block-maxima approach where the annual maximum flow is first taken for each year (Y), then over blocks of five members each (M).*

In this case, an acceptable trade-off was found for blocks of five hydrological years. The 50 CanESM2-LE (40 CESM1-LE) simulations were split into 10 (8) blocks of five members each. For each year of each 5-member block, the flow block maxima are extracted (Figure 8). This led to final samples of 200 and 160 block maxima per 20-year period for CanESM2-LE and CESM1-LE, respectively. While this is a drastic reduction from our initial samples of 1,000 and 800 hydrological years, we considered it preferable to work with larger yet quantifiable parameter uncertainty than with non-quantifiable larger biases related to the fit of the GEV.

The parameters of the GEV distribution were then estimated from the samples of 5-year maxima from each model and 20-year period using the method of maximum likelihood[5]. A transformation was then applied to the parameters to describe annual events instead of 5-year events. These GEV parameters are then used to calculate the 99.9 and 99.99 percentiles, corresponding to events with an annual probability of exceedance of 1:1,000 and 1:10,000, respectively.

The seasonality of flood and the flood volume were both identified by the participants as important aspects that we were not able to include in the methodology. They require a good knowledge of the studied watershed concerning the timing of seasons and also the duration of flood volumes. Both aspects might also change in the context of climate change and need specific analyses at the watershed scale; as a result, we considered these complicated to consider, particularly given the large number of Canadian watersheds of this study. Nevertheless, these aspects are useful for identifying appropriate adaptation options. Indeed, it is quite different to manage a flood occurring during the spring than one during the summer or during the fall, when reservoirs are more likely to have high levels of water.

In summary, here are the main steps of the WG1 method, performed over each watershed.

1. **Calibration of the GR4J+CemaNeige hydrological model based on weather and flow observations**

For each climate model simulation:

2. **Post-processing of the climate simulation against weather observations for daily temperature and precipitation**

For each 20-year period:

3. **Performing hydrological simulations using post-processed climate model simulations as inputs**
4. **Extraction of 5-year block maxima flow**
5. **GEV distribution fit to 5-year block maxima using maximum likelihood**
6. **GEV parameter transformation to describe 1-year maxima**
7. **Computation of the 1,000 – and 10,000-year floods from the fitted and transformed GEV parameters**
8. **Bootstrap resampling with 10,000 draws, and repetition of steps 4–7**

5 To estimate parameter uncertainty, we used bootstrap resampling with 10,000 draws.

Uncertainty-Aware Flood Frequency Analysis – WG2 Methodology

WG2 aimed to develop a general framework for estimating future flood risk while accounting for multiples sources of information and their respective uncertainty. It proposed to include information from nearby watersheds, upstream flow measurements, alternative flow records and hydroclimatic model projections. The main advantage of merging independent sources of information is that random errors cancel each other, leading to estimates that are more accurate. Figure 9 illustrates this process by a simple example, where three measurements and their error distribution are combined to infer the true value. This inference process gives more weight to accurate observations (narrow uncertainties) than to vague measurements (wide uncertainties). WG2 wanted to infer the true value of the GEV parameters describing the likelihood of flow annual maxima.

In general, we implicitly assume that flow observations are exact. In reality, reservoir inflows are often indirectly estimated from an equation balancing daily water-level measurements and total outflow. Total outflow itself can be estimated from measurements at a downstream gauge station, or from hydropower calculations from turbine outputs and spill from sluices. Wind over the reservoir can affect local water-level measurements and give the illusion that water has flowed in or out. Over time, aging turbines lose efficiency and the same water output generates less power. If outflows are estimated from power output, then aging equipment can give the impression that flows are declining. WG2 takes the view that estimating GEV parameters directly from observations, without accounting for these known sources of error, is likely to inspire over-confidence in estimated frequential floods.

To build a picture of extreme flows over time, WG2 used records from: upstream hydrometric gauge measurements; reservoir inflows estimated by water balance; nearby rivers; and simulated flows from hydroclimatic simulations. This work involved defining a probabilistic model[6] integrating various source of information where GEV parameters slowly evolve over time to reproduce the changes seen in climate models and observations.

The uncertainty around measurements stems from various sources. In the case of flow measurements from hydrometric stations, observation errors can arise from ice or debris restricting flow, changes in riverbed morphology, equipment failures or rating-curve extrapolation. Although challenging to estimate, these uncertainties can be mitigated by continuous quality data monitoring from expert hydrologists, and continuous and adaptive maintenance of hydrometric instrumentation. Reservoir inflows are commonly estimated using water-balance equations, where wind effects, equipment aging, reservoir leakage and evaporation can influence calculations, although filtering techniques and quality data-monitoring practices can attenuate some uncertainties. Ideally, a confidence estimate would accompany each measurement. Unfortunately, data providers rarely include uncertainty estimates with observation records.

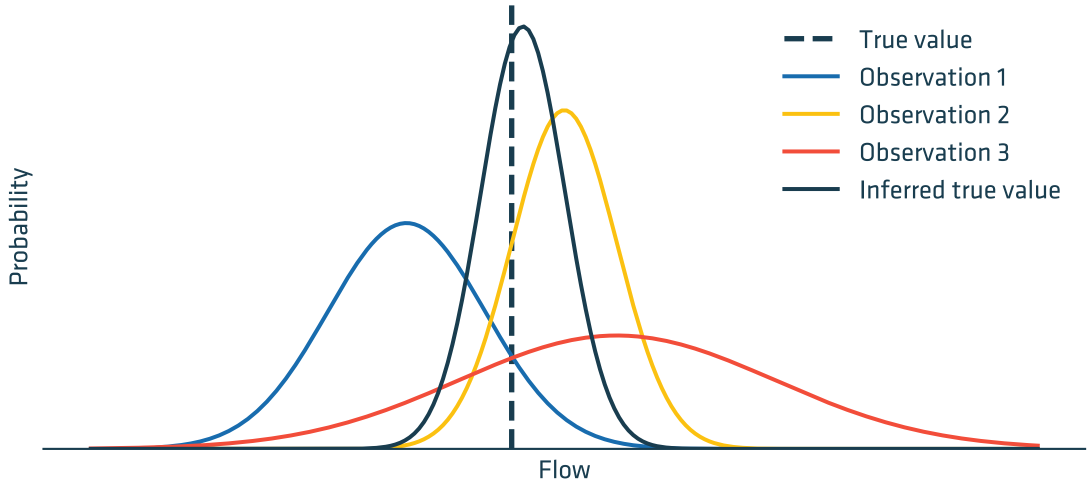

Figure 9: *The true value of some quantity (dashed line) is measured by three observations, each with its own uncertainty (colored lines). Using probability theory, it is possible to combine information from all observations to compute the probability distribution for the true value (black line).*

6 Bayesian analysis is used to define this probabilistic framework, drawing inspiration from Sun, Lall, Merz, & Dung (2015).

To move forward, one solution is to define crude error models: probability distributions providing a simplified representation of the processes behind measurement uncertainties. For example, an error model used by WG2 assumes that modern gauge-measurement errors have a normal distribution around the true value, with a standard deviation equal to 10% of the measured value. This is most certainly an oversimplification, as some hydrometric errors are asymmetric and vary in complex ways according to years and seasons.

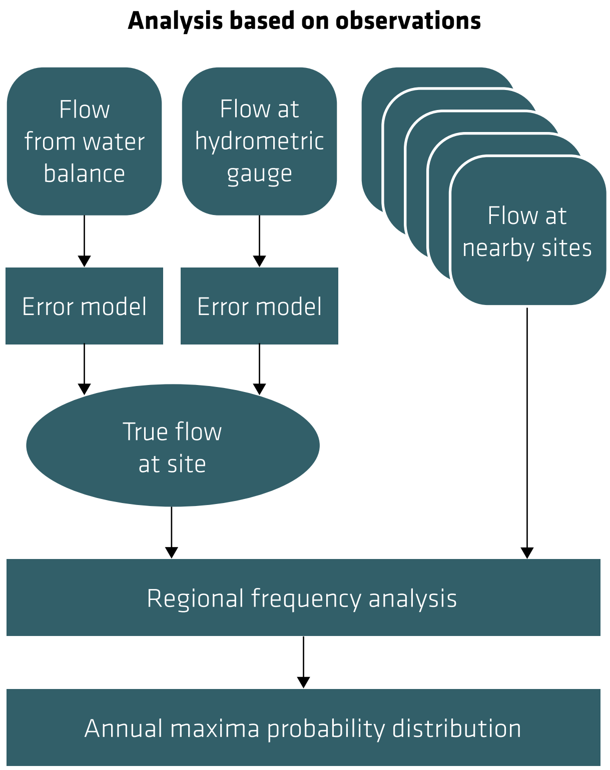

Figure 10: *Information from historical at-site and regional flows informs parameters of the GEV distribution. Time-dependent GEV parameters are inferred from at-site and regional annual flow maxima using probabilistic regional frequency analysis.*

For future flow projections, defining such error models is extremely contentious. Simulated future flows typically depend on the hydrological model and its calibration, land-use scenario, the climate model and the GHGA emissions scenario. There is no consensus on the respective likelihood of the various GHGA scenarios, no obvious metrics to evaluate the performance of climate models to accurately project annual maximum flows, no assurance that model biases will persist in the future, and no guarantee that a hydrological model's current performance will continue in the future. In this context, it is extremely difficult to come up with *a priori* error estimates for flow projection. WG2 thus elected to replace explicit projection error models on projections with an empirical approach based on weights applied to inferred GEV parameters.

Another issue is the relative confidence in observations versus climate projections over time. Given two pieces of information, an historical observed flow record and a future flow simulation, which is more deserving of our trust for 2020–2100? For 2020, the observed record is clearly the most authoritative, but will it still be the case in 2100? At which point do we put more trust in model projections and all their hypotheses than in the historical record? These types of questions must be answered to properly combine historical and projected flows into a single estimate.

To avoid defining complex, time-dependent error models for flow projections, WG2 weighed the GEV parameters estimated from each projection. The parameters inferred from at-site and regional observations are blended with the parameters inferred from model projections according to time-varying weights. This produced a mixed sample of GEV parameters estimated from the historical at-site analysis and the analysis of projections, weighted over time according to user preferences.

The methodology yields a sample of GEV parameters describing the likelihood of observing, over time, annual flow maxima. There are two ways to draw information from this sample. The first, posterior predictive, involves generating GEV distributed random values from the inferred posterior distribution[7] of the parameter set and finding the percentiles of interest (here 99.9% and 99.99%). The second, percentile posterior, involves computing the percentile of interest for each GEV parameter sample. This yields a posterior distribution of percentiles, providing a measure of our confidence in the percentile estimate. Figure 13 illustrates these two approaches. One advantage of posterior predictive is that it provides a single value that accounts for uncertainties, a valuable outcome for risk analysts.

7 In Bayesian parlance, there are prior and posterior distributions, describing our knowledge before and after the data are analysed.

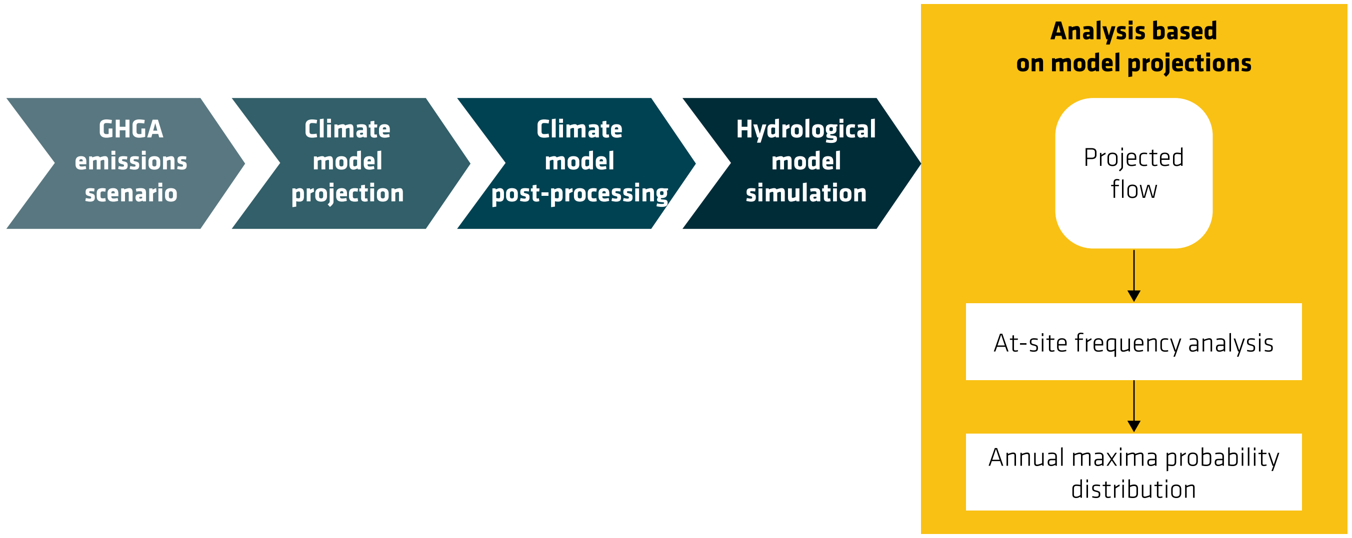

Figure 11: *Information flow from projected flow simulations. For each hydroclimatic model projection, time-dependent GEV parameters are estimated from simulated annual flow maxima.*

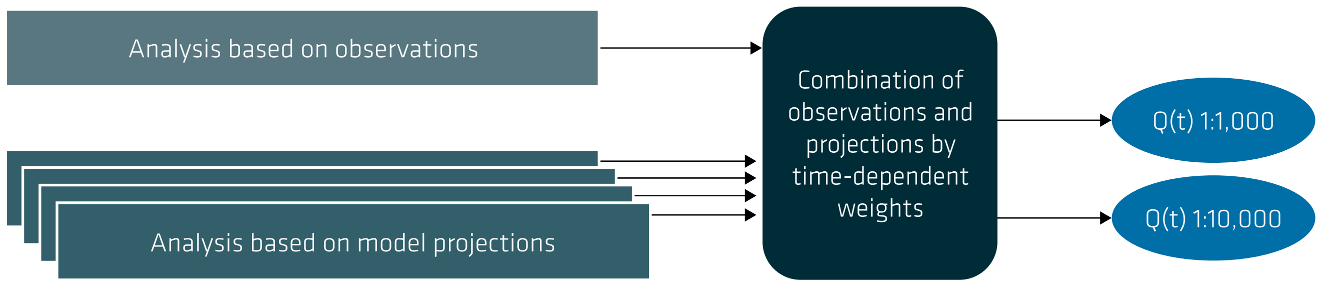

Figure 12: *Combination of historical observations and projections. GEV parameters inferred from regional frequency analysis are combined with GEV parameters inferred from each hydroclimatic model projection using time-dependent weights.*

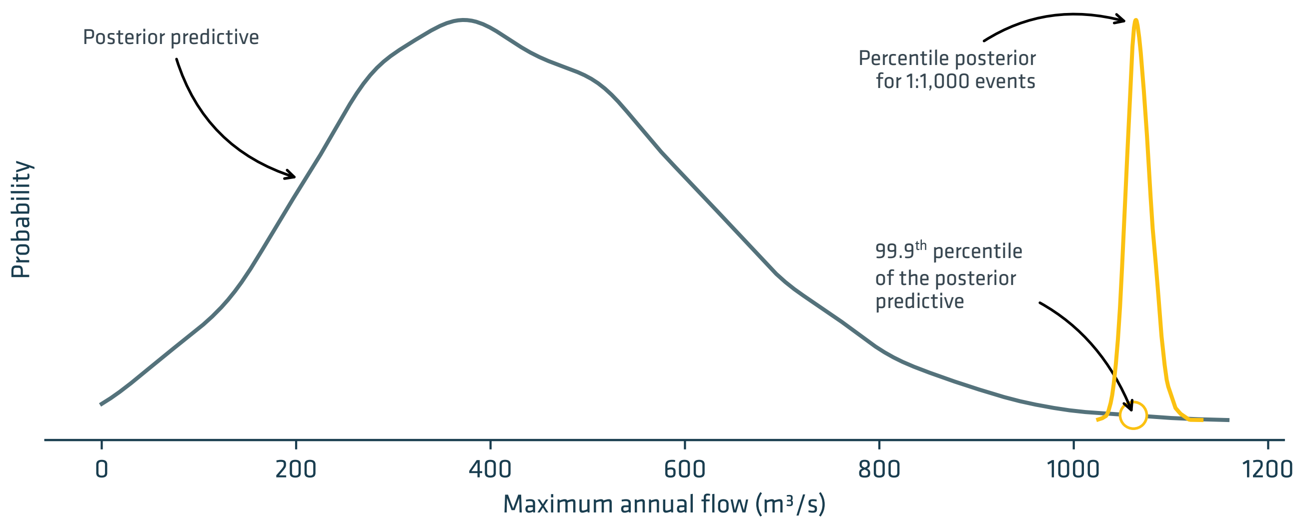

Figure 13: *Conceptual figure showing the posterior predictive of the flow annual maximum (black line) and the posterior distribution (yellow line) for the 1:1,000 percentile. Note that the posterior predictive and percentile posterior are drawn on different vertical scales.*

Risk Metrics in an Evolving Climate

In a stationary context, the return period is well defined. A design value with an exceedance probability of 10% is expected to be surpassed an average of once every 10 years. In a non-stationary context, the relationship between return period and exceedance probability does not hold because for the same event, the probability of exceedance varies over time. To account for this non-stationarity, WG2 suggested using the minimax approach to evaluate design criteria. The minimax design life level is the flow event for which the maximal probability of exceedance in any one year over the design life is at most a given percentage (Rootzén & Katz, 2013). If floods become more extreme over time, then the minimax value will reflect conditions at the end of the design life. On the contrary, if extreme floods become less extreme, the minimax value will reflect conditions at the start of the design life. The minimax criteria essentially scans the entire design life of an infrastructure and extracts the worst-case scenario. Figure 14 illustrates how to compute minimax design life levels from an evolving risk profile.

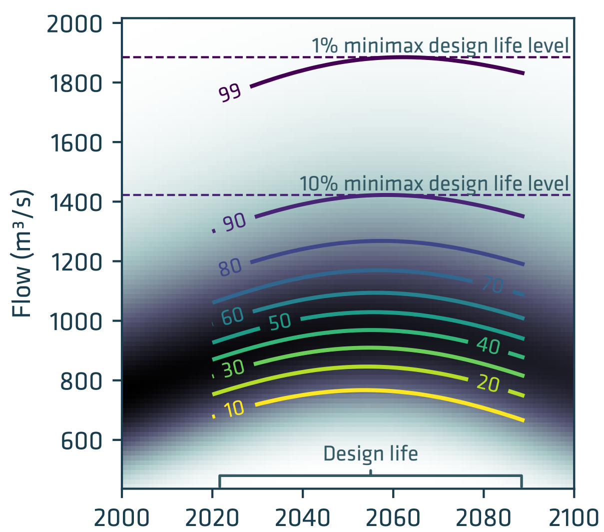

Figure 14: *The minimax design life level is defined such that the maximal probability of exceedance in any one year over the design life is a given percentage. In this example, dotted horizontal lines indicate the 1% and 10% design life levels computed over the design life of the infrastructure. Continuous lines trace the contours of the cumulative density function of annual flow maxima.*

It's worthwhile to note that with the minimax approach, uncertainty directly affects DFV. The probability of exceeding a given threshold reflects not only the reality of underlying hydroclimatic processes, but also our own subjective assessment of uncertainties. To illustrate the point, Figure 15 shows two distributions of annual maxima that account for distribution parameter uncertainties. One is estimated from a sample of 30 values, and the other from a second sample of 100 values, both from the same population. The distribution built from 30 samples is flatter and wider, reflecting the fact that values are less certain. As a consequence of its wider tail, the 99th percentile (circle) for the more uncertain distribution is higher than for the second distribution, and both probabilistic 99th percentiles are higher than the 99th percentiles (triangle) that do not account for parametric uncertainty.

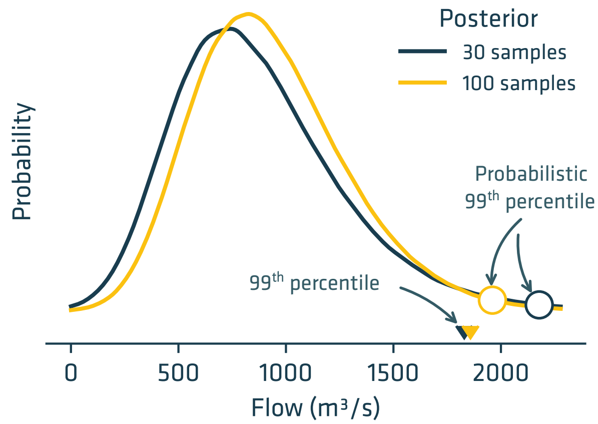

Figure 15: *Posterior probability of annual flow maxima estimated from 30 and 100 samples respectively. Fewer samples leads to higher uncertainty, flattening the distribution and leading to higher values for upper percentiles (circles). The 99th percentiles estimated without accounting for uncertainties (triangles) are smaller.*

Comparison of the Blueprint and the Risk-Averse Flood Frequency Analysis Methodologies from WG1 and WG2

One important difference between WG1 and WG2 approaches is that WG1 analyzes annual maxima over four 20-year periods, assuming that GEV parameters are constant throughout each 20-year period. In contrast, WG2 models GEV parameters as continuously evolving over time from 1950 to 2100[8]. Figure 16 shows results for 2080–2100 2100 (vs 1990-2010 reference period), aggregating WG2's time-dependent results over the 20-year period.

Overall, the results are broadly consistent across methods and datasets in terms of relative change to annual maximum flow (right panels). By better accounting for uncertainty, WG2 yields annual maxima distributions that are wider than WG1 (second vs. first row), which leads to a larger range of possible relative changes. One initially surprising result is the difference in spread between the WG2 results from CanESM2-LE and CMIP5. CanESM2-LE has 50 members, while most CMIP5 simulations have only one member. One would expect that less data in CMIP5 would yield more uncertain results, thus a larger range of relative changes, but the reverse is observed. One explanation is that the CanESM2-LE analysis uses 5-year block maxima, while the CMIP5 analysis uses 1-year maxima, a choice we believe underestimates maxima. This choice was made because taking 5-year block maxima over series of 80 years (4 periods of 20 years) would have led to series of 16 values, too few to estimate three GEV parameters and their temporal evolution. In retrospect, a better solution would probably be to aggregate all the various models into a single probabilistic model, but this would involve further research.

Although results from WG1 and WG2 match fairly well in the case illustrated here, this was not the case for all watersheds and periods, especially when looking at the 1,000 and 10,000-year events. Indeed, results from WG1 fluctuate considerably from one period to the other, while WG2's results vary smoothly over time. The smooth behavior of WG2's results is expected because GEV parameters are constrained to evolve smoothly, but the magnitude of variations across periods for WG1 could not be explained by parametric uncertainty alone. After examination, it appears that these fluctuations from period to period can be attributed to the hydrological model itself and its parameters. Indeed, running similar experiments with other simple lumped hydrological models, or the same model with a different but equally plausible parameter set, yields substantially different 1:1,000 and 1:10,000 events. In other words, the tail end of the GEV distribution is very sensitive to apparently minor changes in hydrological model behavior.

This comparison with WG2 results and the additional modeling experiments that were performed to understand the different results between periods highlight how sensitive 1,000 and 10,000-year flows are to statistical and hydrological modeling hypotheses. Using a simple, single lumped hydrological model has the advantage of facilitating the study of hundreds of watersheds presented in the next section. A disadvantage, due the simplistic hydrological modeling setup, is that the results from individual watersheds would not be robust enough to be used in an actual risk assessment.

Given these uncertainties, and given the project's aim to provide guidelines for risk-averse decision making, the upper end of the WG1 uncertainty envelope (the 90th percentile within the distribution of relative changes) is used in the following as the prudent estimate.

8 In WG2's approach, only the location and scale parameters vary through time, while the shape parameter stays constant. This could lead to an underestimation of future changes in extreme values; relaxing this assumption, however, would require making further hypotheses about the time evolution of the shape parameter.

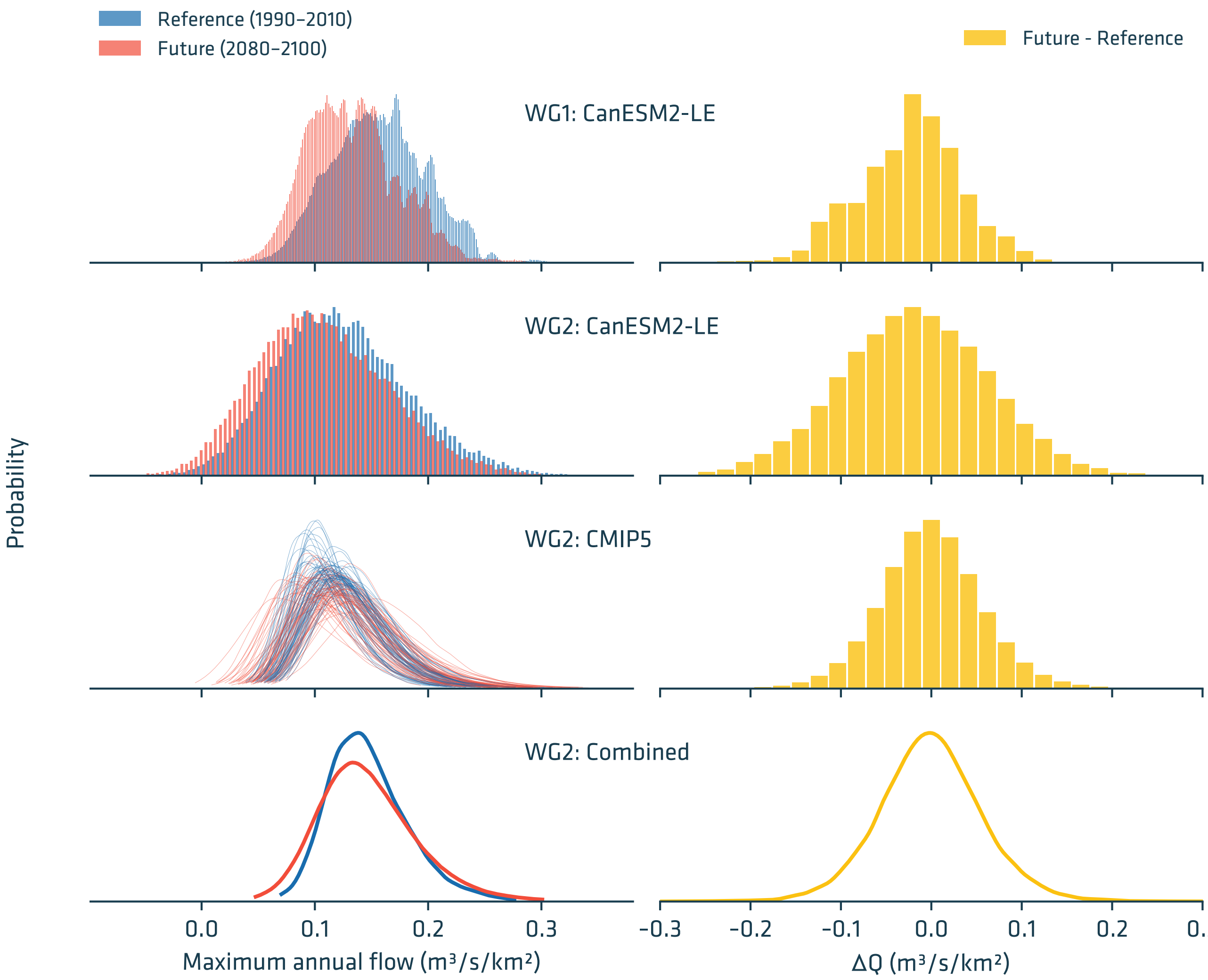

Figure 16: *Comparison of results from WG1 and WG2 on the Kénogami watershed. The left side shows the distribution of annual maxima over the reference (1990-2010) and future (2080-2100) periods, and the right side shows the difference between both. The top panel shows results from WG1's bootstrap uncertainty analysis for CanESM2-LE. The second panel shows results from WG2's approach applied to CanESM2-LE only. The third panel shows results for 69 hydroclimatic model projections, counting 29 different GCMs from CMIP5 driven by up to four GHGA scenarios: RCP 2.6 (9), RCP 4.5 (26), RCP 6.0 (7) and RCP 8.5 (27). The reference and future distributions are shown individually, while the right panel shows the aggregated delta, giving every hydroclimatic simulation a uniform weight. Finally, the bottom panel shows WG2 results where all data sources are combined. This includes at-site and regional observations, CESM1-LE and CanESM2-LE and the CMIP5 projections.*

EXTREME FREQUENTIAL FLOOD RESULTS ACROSS CANADA

The methodological outline from WG1 is applied to 533 watersheds across Canada. Flow annual maxima simulated by GR4J+CemaNeige using CanESM2-LE and CESM1-LE climate scenarios (post-processed outputs) are drawn from Martel et al. (2021). Drawing from the comparison between results from WG1 and WG2, the pan-Canadian results are generated using a slightly modified version of WG1. One difference is that the maps are created only for the 2080–2100 period. The rationale for this choice is that capturing the strongest climate signal possible clarifies the sign of change. Indeed, weak climate change trends are less likely to emerge from the noise on short time scales. Another technical difference is that the GEV parameter estimation is performed by the method of probability weighted moment instead of maximum likelihood. This reduces computational costs and often yields more robust parameters. Finally, instead of looking at the changes between the best estimate over the future and reference period, here we compute the change from reference to future periods for each bootstrap percentile, then take the 90th percentile of the change (see example in Figure 17). This is done to reduce the likelihood of underestimating climate change impacts.

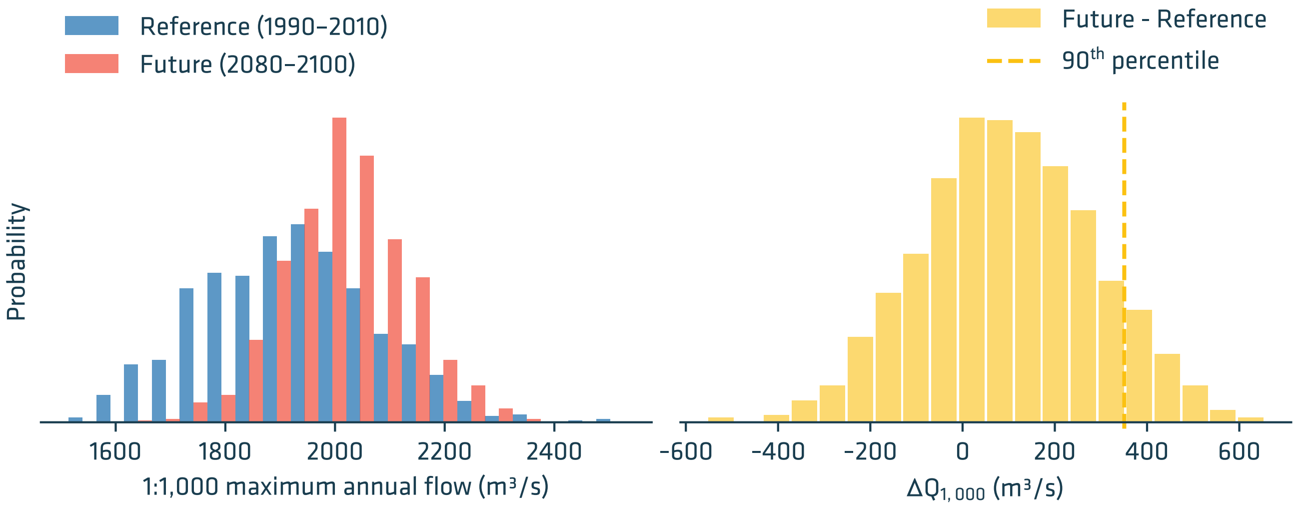

Figure 17: *On the left, histograms of the reference and future annual maximum flow with a 1:1,000 chance of occurring, obtained by bootstrap. On the right, the difference between the future and reference values, with the 90th percentile indicated by a vertical line. Values shown are from the Ashuapmushuan watershed and CESM1-LE climate ensemble.*

Maps of Change in Frequential Floods across Canada

The relative change in 1:1,000 and 1:10,000 flood events over the 2080–2100 period relative to the reference (historical; 1990-2010) period are mapped for CanESM2-LE in Figures 18 and 19. The relative change is computed as:

$$\Delta = \frac{\text{future} - \text{reference}}{\text{reference}} \times 100$$

and colour-coded for each watershed. Watersheds where both large ensembles agree on the sign of change are indicated by hatching.

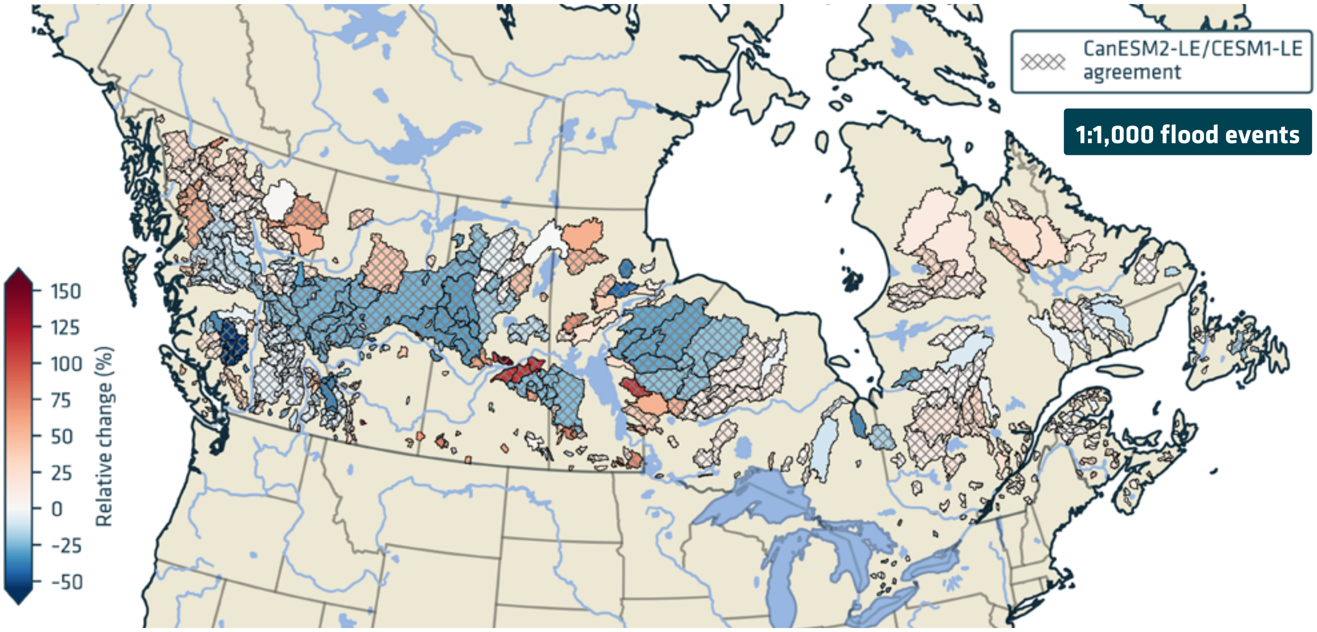

Figure 18: *Relative change, between 1990–2010 and 2080–2100, in 1:1,000 flood events across Canada estimated using WG1's approach applied to CanESM2-LE and using the 90th percentile of the bootstrap sample.*

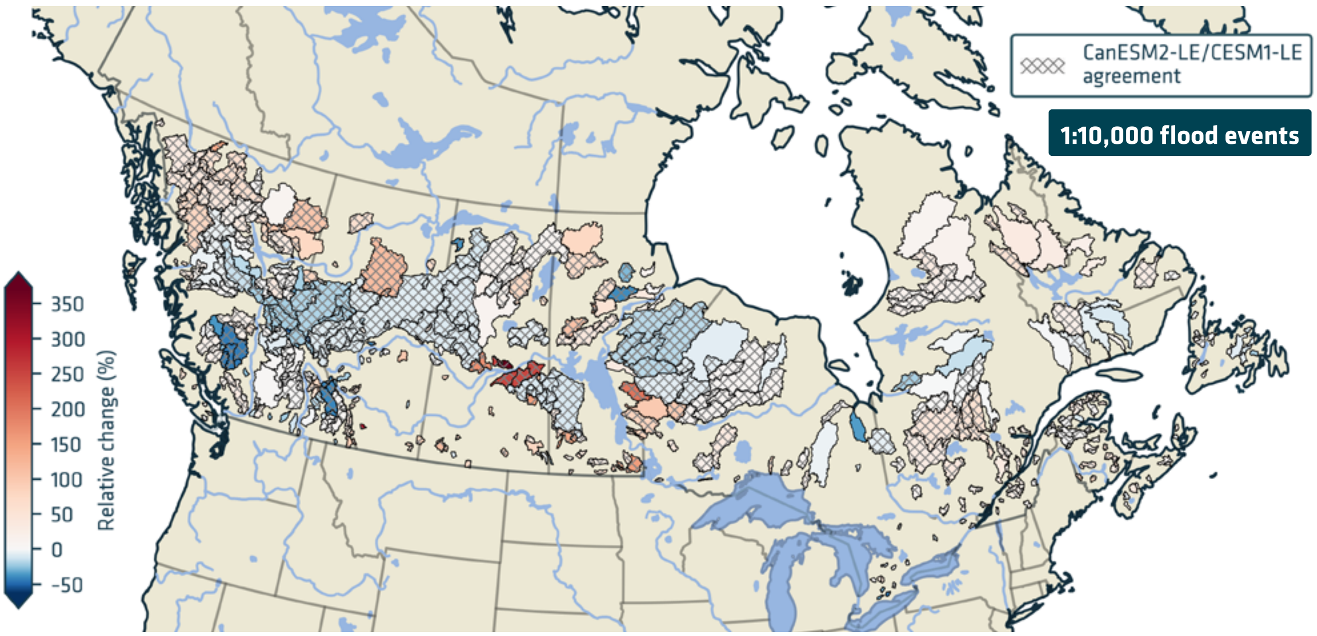

Figure 19: *Relative change, between 1990–2010 and 2080–2100, in 1:10,000 flood events across Canada estimated using WG1's approach applied to CanESM2-LE and using the 90th percentile of the bootstrap sample.*

DAMS IN THE 21ST CENTURY – ADAPTATION OPTIONS

Context

While both WG1 and WG2 provided methods to evaluate climate change impacts to Design Flood Value (DFV) estimates, it was the task of WG3 to develop a method/tool for dam owners to consider these climate impacts and identify solutions to adapt to the projected changes. This task was a challenging endeavor on several fronts.

Dam safety management is traditionally carried out by assuming hydroclimatic stationarity over the asset's functional life. Regulators and related institutions increasingly acknowledge the impacts that climate change may have on dam safety. However, there is limited guidance about how to include future climate risk in the safety management of existing and planned structures (CDA, 2007; FEMA, 2013; IHA, 2019). Some organizations have begun to draft climate change adaptation policies. However, much of this work remains preliminary (e.g., USACE, 2014, 2016; USBR, 2014) and largely focuses on updating planning processes to formally recognize and consider the need to consider climate change risks, rather than on prescriptive methodologies for adaptation planning.

It is very important to recognize that the design of adaptation solutions is highly dependent on both the watershed/regulated system operating constraints and at-site/structure specifics. While system regulation adds to the complexity of evaluating climate change impacts, modification of system regulation, or Operational Adaptation serves as an initial "low-regret" option to manage potential hydroclimatic change.

In instances where operational adaptation alone is not able to accommodate future hydroclimatic change, Structural Adaptation represents a secondary method of addressing projected climate change impacts. The modification and retrofitting of structures to accommodate larger floods is well established in the dam safety community; however, these options tend to be more costly and require a significant effort to plan, design and construct. Additional factors such as environmental licensing and long-term operation can also limit the feasibility and desirableness of these types of options.

Finally, Regulatory Adaptation can be considered a third means of accommodating the added risk of hydroclimatic change at a particular site. This type of adaptation strategy focusses on re-considering the basis of a structure's Design Flood Value (DFV) and its mode of operation, recognizing that both criteria have been formulated on the fundamental simplifying assumption of hydroclimatic stationarity.

Operational Adaptation

To illustrate the challenge of adapting existing structures, consider the hypothetical case of a reservoir facing significant increases in water levels (peak and volume) due to climate change. To increase the storage capacity needed to mitigate flood risk, a low-regrets (i.e. low cost and large benefit) adaptation strategy is to lower the normal operating level year-round. This adaptation option mitigates the added risk of a larger DFV, but would likely decrease the structure's operational performance and generating capacity under current climate conditions, and therefore may not be a true low-regrets solution. Nevertheless, it demonstrates the potential to implement an effective adaptation option without making physical changes to existing infrastructure.

This simple case is not representative of most watersheds and networks facing the challenge of climate change adaptation, however. Most of these feature a network of multiple reservoirs managed by complex systems and policies to optimize performance and meet the needs of various stakeholders. Despite these added complexities, operational adaptation to climate change is still a viable solution. In recent years, MELCC has successfully deployed interdisciplinary projects in three of its dam-managed watersheds to evaluate adaptation to climate change (Lachaut & Tilmant, 2020; Tilmant, Lachaut, Mercille, Marceau, & Faucher (2019) for the upper Saint-François watershed).

For example, reconsidering flood risk at a site by moving from a standards-based DFV to risk-informed DFV may determine that its existing flood-conveyance capacity is adequate under future climate conditions. Similarly, having open communication and discussion with stakeholders to discuss the trade-offs between operating constraints to accommodate their interests vs. enhanced climate resilience may lead to new or enhanced operation-adaptation solutions. Naturally, the implementation of these solutions requires acceptance and endorsement by regulatory agencies and stakeholders. Therefore, the feasibility of implementation will vary widely.

The many specificities of the previously mentioned adaption options limit the feasibility of developing a one-size-fits-all approach to addressing climate change impacts. Data availability regarding design flood estimates and station performance also influence the level of detail/complexity feasible for a given site. The adaptation solutions to consider thus require a level of flexibility to accommodate the vast range of conditions that could be anticipated.

Objectives and Constraints

At a high level, the work of WG3 was based upon the premise that a given dam has the capacity to safely withstand/manage a specified flood risk (i.e. the DFV); however, there also exists a critical threshold or magnitude of flood that the structure can no longer safely accommodate. WG3's efforts focused on developing an approach for dam owners to use the outputs of WG1 and WG2 to: (1) understand how climate change may impact the risk of future floods exceeding a structure's critical threshold; and (2) to identify feasible adaptation option alternatives that manage the potential change in risk described in these future climate scenarios.

The approach adopted was intended to be flexible enough so that it could be used by dam-safety practitioners in a variety of contexts in terms of:

- The relative availability and richness of existing hydrotechnical studies/tools and DFV estimates for the structures of interest;
- The type of future climate scenario information available (peak flows, flood volumes, etc.) and description of uncertainty;
- The adaptiveness of the reservoirs' management to incremental alternative management policies which could improve adaptation, ideally through no-regrets approaches;
- The adaptiveness of hydrostructures' physical features in terms of structural upgrades or design adjustments;
- The open-mindedness of stakeholders to consider new ways of addressing the management constraints, including their acceptance of some loss of performance for the benefit of an increased robustness to climate change impacts.

It became evident that high-level screening would be an ideal approach to the problem, as many acknowledged that it would likely be their first attempt to solve the adaptation problem, and that it would be conducted with the limited information and resources available. Similarly, it was recognized that in some cases, future flood risk for a given dam/structure would be highly dependent on the network response to climate change. Despite the limitations described above, employing a high-level screening methodology as an initial step provided valuable information and context to guide the scoping of more comprehensive and deep-dive quantitative studies that a dam owner may wish to conduct to refine their preferred adaptation alternative.

Regulatory Standards vs Risk-Informed Approaches to Dam Safety

Safety management is ultimately concerned with the management of risk; identifying what can go wrong, and its likelihood and potential consequences (CDA, 2013).

The traditional approach to dam safety hydrological assessment is standards-based. It features conservative safety factors designed to minimize risks to downstream communities. Most regulatory frameworks in Canada align with the Dam Safety Guidelines produced the Canadian Dam Association (CDA). The safety factor described in the Guidelines as the inflow design flood is referred to in this report as design flood value (DFV). The DFV of a dam is determined by classifying the level of potential consequences (e.g. low, high, extreme) of its failure. Consequences include potential deaths. For a low consequence dam, the CDA Guidelines (Canadian Dam Association, 2013) recommend designing for a 1:100 event. If the consequence classification is very high to extreme, the Guidelines recommend the dam be designed to accommodate a DFV of a 1:10,000 event or the probable maximum flood (PMF). In some jurisdictions, regulations are enshrined in legislation and typically follow a deterministic statistical approach to identify 1:1,000 and 1:10,000-year events.

A risk-informed approach, encouraged by the CDA (Canadian Dam Association, 2013), characterizes various undesired events in terms of their likelihood and potential consequences. It considers many factors, such as flow, structural performance, safety margins, human factors and operations, and involves failure modes analysis. The approach treats risk tolerance as a policy choice to be explicitly expressed by clearly identifying trade-offs between economic efficiency and social equity. Its underlying goal is that risks associated with dams should be as low as reasonably practicable. Although this approach requires a more intensive analysis, it enables owners and regulators to balance multiple risks and dedicate resources to where they are most needed to achieve the desired safety outcomes (Canadian Dam Association, 2013).

Adopted Approach

In pursuit of the objectives described previously, WG3 adopted a high-level screening-study methodology. This method identifies a structure's relative vulnerability to climate change within a watershed and generates a basic set of conceptual alternative options that subsequent studies can consider to improve resiliency. Guidance from *Global Climate Change, Dams, Reservoirs, and Related Water Resources (ICOLD, 2016)* and *Climate Risk Informed Decision Analysis (CRIDA): Collaborative Water Resources Planning for an Uncertain Future* (UNESCO and ICIWaRM, 2018) was used to formulate WG3's methodology.

Figure 20 illustrates, at a high level, the five main steps that WG3's methodology follows.

Figure 20: *WG3 Methodology.*

The four-scenario framework identified by ICOLD (2016) (Figure 21) was used to evaluate the performance and feasibility of potential operational and structural adaptation options in Step 4 of the methodology.

Scenario 1 Reference climate	**Scenario 2** Future climate	**Scenario 3** Future climate + operational adaptation	**Scenario 4** Future climate + operational adaptation + structural adaptation
Current climate	Projected climate	Projected climate	Projected climate
Current DFV	Projected DFV	Projected DFV	Projected DFV
Current operating rules	Current operating rules	Adapted operating rules	Adapted operating rules
Current stuctural configuration	Current stuctural configuration	Current stuctural configuration	Adapted structural configuration

Figure 21: *The four-scenario framework, each scenario consisting of 4 steps, to evaluate potential adaptation options (from ICOLD, 2016).*

Example Case Study: Winnipeg River Watershed Generating Station

As an illustrative example, the methodology of WG3 as applied to an existing generating station in the Winnipeg River watershed is described below.

Figure 22: *Winnipeg River Generating Station Case Study.*

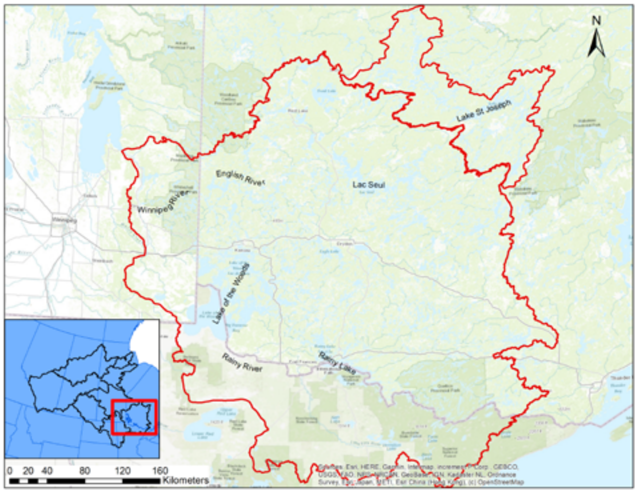

Figure 23: *Winnipeg River Watershed.*

The Winnipeg River watershed is located in the eastern portion of the Canadian Shield, covering a large area of northwestern Ontario, and smaller portions of southeastern Manitoba and northern Minnesota. The watershed drains an area of approximately 150,000 km^2, emptying into Lake Winnipeg. From there, water flows north into the Nelson River and eventually into Hudson Bay. Featuring many lakes and large forested areas, the watershed generally has shallow soils overlaying bedrock. While sparsely populated, it is home to large pulp-and-paper facilities, several First Nations communities, seasonal cottage areas, and a thriving tourism industry. The watershed has a long history of hydroelectric development and regulation; several generating stations were constructed near the turn of the 20th century.

The case study focuses on an aging but well-maintained structure characteristic of many generation stations in the watershed. The dam lies near a sizeable townsite, First Nations reserve and many seasonal cottages. The forebay of the generating station has a tight operating range with minimal live storage; the operations of upstream control structures and generating stations (owned by multiple agencies) strongly influence inflows. The generating station continues to be economically viable and there are no plans to decommission it in the foreseeable future.

Step 1: Reviewing Current DFV and Critical Threshold

Based on CDA guidelines, it is classified as a Significant dam and must withstand the 1:1,000 DFV. The most recent safety reports and studies indicate that it complies with this, although some surcharging above the station's full supply level is required. The most recent safety review noted that the dam's DFV classification may increase to high, depending upon a future review of dam failure consequences.

Based on this information, it was determined that the existing DFV should be adopted as the critical threshold; any increase in future flood risk would potentially require adaptation measures.

Step 2: Examining Climate Change Impacts and Identifying Level of Concern

Future climate projections relevant to the Winnipeg River generating station's DFV are summarized in Tables 1 and 2.

Table 1: *Projected relative change to annual maximum flood with respect to the reference period (1981–2000) estimated by WG1.*

Annual Exceedance Probability	Relative Change (%) 2031-2050		Relative Change (%) 2051-2070		Relative Change (%) 2081-2100	
	CanESM2-LE	CESM1-LE	CanESM2-LE	CESM1-LE	CanESM2-LE	CESM1-LE
1:100	-8	-1	-4	-4	-1	-11
1:1,000	-12	5	-4	-3	2	-7
1:10,000	-17	12	-4	-2	5	-3

Table 2: *Projected relative change in minimax design criteria estimated by WG2 from the posterior predictive of observations and the combination of observations, and CMIP5 ensemble projections for three probability thresholds evaluated over the period 2000–2050.*

Annual Exceedance Probability	Relative Change (%) 2000–2050
1:100	-6
1:1,000	-3
1:10,000	-7

The results summarized above demonstrate a high level of uncertainty associated with project changes to the site's DFV. Adopting a conservative estimate from WG1, one might adopt a 5% increase to the DFV as the worst-case scenario for this structure. However, looking at the range of potential impacts and WG2's results, this increase is uncertain. It is also worth noting that for this particular location, annual maximum flood did not consistently occur in the spring period; uncertainty about flood type and timing may influence flood risk. The results highlight that climate change imposes significant uncertainty on an already uncertain extreme value.

Step 3: Exploring Adaptation Options

To explore the range of potential adaptation options, a brainstorming session was organized among a team of subject matter experts (SMEs) in dam safety, along with engineers from various disciplines (hydraulic, hydrologic, structural, geotechnical, environmental) familiar with the site. To help guide the session, a list of potential adaptation options was prepared, separated into three main categories:

- Operational Adaptation
- Structural Adaptation
- Regulatory Adaptation

The adaptation options presented in the spreadsheet were derived from studies conducted at the site, dam-safety reviews, and from reviews of relevant SME research and literature, including *Probable Maximum Floods and Dam Safety in the 21st Century Climate* (Ouranos, 2015).

For each adaptation option listed on the spreadsheet, corresponding columns documented discussions about:

- General pros and cons
- Feasibility
- Desirability and practicality
- Range of flow accommodation
- Flexibility of implementation
- Past experience and potential stakeholder concerns

Working from existing studies and past experience, the brainstorming team populated the spreadsheet. During the session, fewer details were gathered for options identified as neither feasible nor desirable. Among options identified as feasible and desirable, some were noted as requiring additional study and consultation with other SMEs due to the team's relative lack of relevant experience and/or expertise on the matter.

Step 4: Evaluating Performance and Feasibility of Adaptation Options

Given available climate change projections and the brainstorming discussions, adaptation options were screened and categorized based on feasibility of implementation and ability to accommodate future flood risk. All of the options presented in Table 3 achieve a reasonable level of performance under existing climate conditions.

Table 3: *Evaluation of Adaptation Option Performance and Feasibility for Winnipeg River Watershed Generating Station.*

Most Realistic/Feasible Adaptation Options	Less Realistic/Possibly Feasible Options	Unrealistic/Infeasible Adaptation Options
Structural Adaptation ▷ Service spillway modifications ▷ Auxiliary spillway construction **Regulatory Adaptation** ▷ Review of dam classification and DFV estimation ▷ Risk-based DFV determination	**Structural Adaptation** ▷ Raising dam/dyke embankments ▷ Unit re-runnering	**Structural Adaptation** ▷ Spillway replacement ▷ Decommissioning ▷ Channel improvements **Operational Adaptation** ▷ Not enough live storage at site to accommodate larger DFV (even by lowering reservoir level) ▷ Largest storage/regulation controlled upstream by other agencies

Since any increase in DFV could push the study site past the critical threshold and lead to hazard reclassification, the most realistic adaptation options were to increase spill capacity (Structural Adaptation) and/or review the overall methodology for DFV selection and calculation (Regulatory Adaptation). While modification of reservoir operations would be a desirable low-regrets options to accommodate a larger DFV (Operational Adaptation), this particular structure has a very small reservoir with minimal storage available to attenuate floods. Similarly, since federal and international agencies regulate the large upstream reservoirs capable of providing flood attenuation, re-regulation was deemed infeasible for the purposes of this initial evaluation.

Step 5: Identifying Preferred Adaptation Strategy for Further Consideration

While the results of WG1 showed the potential for significant added risk due to a larger DFV in the future (up to a 5% increase), the analysis from both WG2 and WG1 resulted in a high degree of uncertainty in future impacts to these extreme flood scenarios. Using the decision matrix developed by CRIDA manual (Figure 24), it was evident that given the level of future risk and associated analytical uncertainty, robust and flexible adaptation options would likely be the most strategic choices for further study and evaluation (Quadrant IV).

A challenge with this site is that very few robust and flexible actions can be implemented immediately. While Operational Adaptation would be a desirable low-regrets way to address uncertain (but potentially significant) future risk, site characteristics limited feasibility of options in this category.

The brainstorming session for Step 3 did, however, identify some Regulatory Adaptation options that may be capable of addressing the increased but uncertain future risk of climate change. For example, a risk-informed approach to DFV selection might determine that existing total spill capacity is adequate. While such an approach would require significant investment and technical analysis, the overall costs might be less than any Structural Adaption option, and a much richer and more comprehensive understanding of the station's resiliency to existing and future risks would be gained. Even if the risk-informed DFV approach still identified a need for additional spill capacity, this type of adaptation strategy might improve the effectiveness and performance of any Structural Adaptation option.

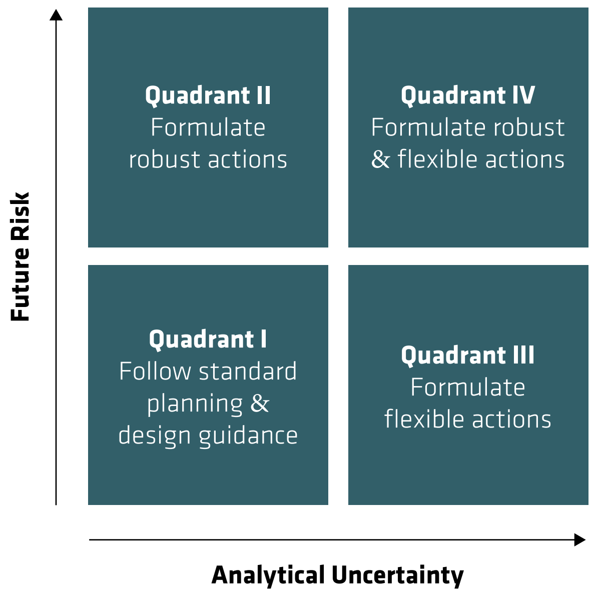

Figure 24: *Decision Matrix for Adaptation Strategy Selection, adapted from CRIDA (UNESCO and ICIWaRM, 2018).*

Notwithstanding the potential benefits, following a risk-informed approach might not preclude the need to increase flood capacity. The analysis conducted in Step 3 identified two potential Structural Adaptation options worthy of further study: retrofitting a fuse gate in a currently unused log chute; and converting a non-overflow section of the dam into a broad-crested weir section. Both options could handle a wide range of future flow increases, would require a relatively low level of ongoing maintenance and could be implemented in a fairly flexible way without impeding or hindering existing operations under existing hydroclimatic conditions.

Additional monitoring and analysis might also improve understanding of current flood risk and help identify the point when these structural changes must be implemented. Monitoring for changes in extreme events is a challenging task; however, additional observation data and future climate change scenarios may increase knowledge about future impacts and strengthen the justification to implement robust solutions.

Detection and Attribution for Hydrological Extremes

Detection and attribution (D&A) is a branch of climate science focused on the causal links between observed climate and natural and anthropogenic forcings, such as GHGA emissions and land-use changes. Detection involves extracting climate change signals (e.g. air temperature trends) from the background noise of natural climate variability. Attribution involves identifying the causes of a given change. Attribution techniques can, for example, help identify the phenomena driving a major flood: abnormal rainfall, exceptional snow cover, antecedent soil moisture, frozen soil, or some combination of these. It can also assess how likely the event would have been under pre-industrial conditions, quantifying anthropogenic influence. D&A studies may look at long-term global phenomena, such as temperature trends and sea-level rise (Bindoff et al., 2013), or delve into regional patterns. For example, a study in the western U.S. detected a change in the timing of snowmelt-driven flow that could be confidently attributed to anthropogenic GHGA and land-use changes (Hidalgo et al., 2009).

D&A studies can also focus on individual extreme events, such as heatwaves, droughts and floods. In Canada, event-attribution studies were conducted of the 2013 Alberta flood (Teufel et al., 2017) and the 2017 Montreal flood (Teufel et al., 2019). By running regional climate-modeling experiments with different initial soil conditions, atmospheric moisture and snow cover, as well as by comparing current-day precipitation with simulations of pre-industrial conditions, the studies identified the mechanisms driving these floods, along with the probable influence of climate change. While climate change's influence (fingerprint) is found in the increasing intensity and frequency of heavy rainfall, the competing effect of reduced snow cover and slower snow melt (Musselman, Clark, Liu, Ikeda, & Rasmussen, 2017) act to blur the influence of climate change on peak flows. Although confidence in detecting and attributing trends in snowmelt-driven floods to climate drivers was assessed as medium, understanding the underlying causes of extreme events can help focus monitoring efforts on the phenomena most likely to cause future damage.

CONCLUSION AND RECOMMENDATIONS

This project started with the naïve hope that climate model outputs could directly provide information about expected changes in DFVs. We thought that proxies, possibly based on precipitation or runoff simulated by climate models, could give a measure of relative changes in peak floods due to rising GHGA emissions. These hopes were rapidly dashed. The spatial resolution of climate model runoff leads to unrealistic peaks flows, and the influence of snow-melt processes invalidates any shortcut based on precipitation alone. Without a full modeling chain that includes hydrological models calibrated to the target watershed, practitioners would not trust the results.

The project thus tried to find a pragmatic approach to DFV estimation that incorporates climate change, by: leveraging simple parsimonious hydrological models that can be calibrated unsupervised; using large ensembles of climate model simulations; and by using the generalized extreme value distribution with 5-year block maxima (an original twist on frequency analysis). While these adjustments make it possible to apply the approach to hundreds of watersheds, the hydrological model used and its automated calibration are too simplistic to draw robust conclusions about the impact of climate change on individual watersheds, and cannot replace a genuine site-specific frequency analysis.

That said, even a detailed analysis of a single watershed would face challenges. The interplay between snowpack, melting and precipitation intensity might lead to increases up to a certain future time horizon, then a decrease. Different hydrological models, calibrated using the same observation datasets, can yield opposite climate change responses. Statistical extrapolation to very-high percentiles further magnifies each source of uncertainty. For example, the same hydrological model run with two equally plausible parameter sets can, in some cases, yield opposite climate change responses for 1:1,000 or 1:10,000 flood events. This poses particular challenges for responsible dam owners who strive to integrate climate change into asset-management decisions for existing facilities.

In fact, traditional frequency analysis is not immune to uncertainty. Indeed, measurement errors affect observed flow series and the uncertainty related to the parameters of a statistical distribution has a very large influence on extrapolation to extremely rare events. Clearly, this uncertainty has not been an obstacle to frequency analysis informing regulations and standards. Indeed, regulatory regimes typically use a standards-based approach, where dam owners are required to have the capacity to pass a particular magnitude flood (i.e. 1:10,000 event).

The reality of climate change has now introduced a paradigm shift, invalidating the traditional assumptions of stationarity in extreme event analysis. The dam safety industry recognizes the need to include both risk management and standards-based approaches; in 2018, Alberta updated its regulatory framework related to the risks and hazards posed by a structure and the assignment of consequence classification (https://www.alberta.ca/dam-and-canal-safety-regulatory-framework.aspx). The CDA's Dam Safety Guidelines serve as guidance for regulated provinces (Alberta, B.C., Quebec and Ontario) and a source of best practices for non-regulated provinces and territories. These guidelines, nationally and internationally recognized as good practices, include approaches based on both risk management and standards (see Regulatory Standards vs Risk-Informed Approaches to Dam Safety Inbox).

To account for the inherent uncertainty and non-stationarity introduced by changing environmental and climatic conditions while continuing to meet existing goals for standards-based dam safety, regulatory updates are required. While current hydroclimatic science might not provide the confidence required for a standards-based approach to climate change impact assessment, the magnitude of projected future changes in precipitation and snow patterns across the country suggests that flood-risk analyses should consider the influence of climate change.

This study explores some of the challenges posed by climate change and the estimation of extreme events for dam-safety purposes. The results show spatial and temporal dependence on the magnitude of 1:1,000 and 1:10,000 flood events across Canada. For most watersheds, CanESM2-LE and CESM-LE agree on direction of change, but not surprisingly differ on the magnitude of a flood event for a given confidence interval and estimation method. This poses particular challenges for responsible dam owners who strive to integrate climate change into asset-management decisions for existing facilities.

CDA first published Dam Safety Guidelines in 1995 (and revised them in 1999, 2007 and 2013). Regulatory updates are required to continue to meet the intent of existing standards-based dam safety regulations, but account of the inherent uncertainty and non-stationarity introduced by changing environmental and climatic conditions. The migration to risk informed dam safety processes would allow dam owners the flexibility to balance the changes in risks introduced by climate change and the constraints of adapting a pre-existing dam.

This migration to risk-informed dam safety would open the door to a richer set of approaches to flood-risk analysis. Based on the results of this project, we propose a few recommendations regarding the evaluation of future flood risks:

- Estimating future flood risks requires hydrological models calibrated to reproduce seasonal and/or annual floods. Model uncertainty should be quantified by creating multi-model ensembles, or parameterization ensembles (multiple sets of equally plausible parameter sets).
- In some watersheds, intense summer or fall rain, rather than spring melt, might drive future annual peak floods. Frequency analysis should clearly differentiate peak floods driven by snow-melt from those driven by rain. This also applies to flood volume, often needed to conduct dam-safety assessments.
- Until the scientific community assigns probabilities to future GHGA emissions scenarios, risk analyses should consider at least low-end and high-end scenarios.
- An array of climate models should be used to drive hydrological models. The climate models should span a range of climate sensitivities (the temperature response to a doubling of GHGA concentration) and ideally feature multiple realizations to provide a measure of natural climate variability.
- Extrapolation to rare events should rely on extreme-value distributions. Other distributions might better fit the mode of the distribution, but fail to guarantee the realism of extrapolation to very rare events. In any case, results should integrate distribution parameter uncertainty.

The consideration of climate change impacts in design flood estimation and adaptation planning is a challenging, but necessary endeavour. Dam-safety practitioners are entrusted with protecting the public and environment from the effects of dam failure and are required to exercise due diligence at all stages of a dam's lifecycle. While significant uncertainties are associated with the risks imposed by climate change on dams, owners must accept the challenge of considering these impacts in the design and operations of these critical infrastructures. Dam safety has a rich history of managing the uncertainties of extreme events by harnessing new information and methods that establish and refine best practices. Climate change is merely the latest chapter in this ongoing history, and practitioners must now consider the uncertainties of both the past and future to ensure that the dams they design, own and operate are safe for future generations.

ACRONYMS

ALARP	As low as reasonably practicable
AM	Annual maximum
CDA	Canadian Dam Association
CanESM2-LE	Canadian Earth System Model version 2 Large Ensemble
CESM1-LE	Community Earth System Model version 1 Large Ensemble
CMIP5	Coupled Model Intercomparison Project Phase 5
CRIDA	Climate Risk Informed Decision Analysis
D&A	Detection and Attribution
DFV	Design Flood Value
GCM	Global Climate Model
GEV	Generalized Extreme Value
GHG	Greenhouse gases
GHGA	Greenhouse gases and aerosols
GR4J	Modèle génie rural à 4 paramètres journalier
HYSETS	Hydrometeorological Sandbox École de technologie supérieure (ETS)
ICIWaRM	International Center for Integrated Water Resources Management
ICOLD	International Commission on Large Dams
IHA	International Hydropower Association
MELCC	Ministère de l'Environnement et de la Lutte contre les changements climatiques du Québec
NRCan	Natural Resources Canada
OPG	Ontario Power Generation
PMF	Probable Maximum Flood
RCP	Representative Concentration Pathway
SMEs	Subject Matter Experts
WG	Working Group

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