REPORT

Fraser Basin Council

Investigations in Support of Flood Strategy Development in B.C. B-1: Impacts of Climate Change

MARCH 2021

A Carbon Neutral Company

BEST MANAGED COMPANIES Platinum member

CONFIDENTIALITY AND © COPYRIGHT

This report was prepared by Associated Engineering (B.C.) Ltd. on behalf of Fraser Basin Council. The material contained in it reflects Associated Engineering (B.C.) Ltd.'s best judgement, in the light of the information available at the time of preparation. Any third party use of this report, or any reliance on or decisions made based on it, are the responsibility of such third parties. Associated Engineering (B.C.) Ltd. accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this report.

Associated Engineering (B.C.) Ltd.
#500 - 2889 East 12th Avenue
Vancouver, B.C., Canada, V5M 4T5

TEL: 604.293.1411
FAX: 604.291.6163
www.ae.ca

March 19, 2021
File: 2020-2894-00

Frances Woo
Program Manager, Flood Strategies
Fraser Basin Council
1st Floor, 470 Granville Street,
Vancouver, BC V6C 1V5

Re: INVESTIGATIONS IN SUPPORT OF FLOOD STRATEGY DEVELOPMENT IN BC
B-1: IMPACTS OF CLIMATE CHANGE

Dear Frances:

We are pleased to submit our investigative report for Issue B-1: Impacts of Climate Change. This report is part of a province-wide initiative aimed at developing a comprehensive understanding of current challenges and opportunities relating to flood management across BC. Issue B-1: Impacts of Climate Change falls under Theme B – Flood Hazard and Risk Management of the larger initiative.

Thank you for the opportunity to work on this interesting project. We trust the findings of this report will provide valuable insight and support for developing a Flood Strategy for BC. Please feel free to contact us if you have any questions or concerns related to this report.

Yours truly,

Jeremy Fyke, Ph.D
Project Manager Manager - Climate Services Group

John van der Eerden, M.Eng. P.Eng
Vice President - Water Resources

JF/JvdE/lw

A Carbon Neutral Company

CANADA BEST MANAGED COMPANIES Platinum member

EXECUTIVE SUMMARY

This study, **B-1: Impacts of Climate Change,** supports improved integration of climate change considerations into flood planning in British Columbia. It does so by assessing the current state, capacity, and approaches to assess the most prominent flood hazards that are, or could be, impacted by a changing climate, namely:

- Riverine Flooding caused by spring freshet, atmospheric rivers and/or ice jams.
- Coastal flooding caused by sea level rise and storm surge.
- Pluvial flooding caused by intense local precipitation.
- Compound event flooding due to a combination of individual flood mechanisms.

Within each flood type listed above, this report includes specific investigations that focus on the following issues:

B-1.1: Current state of understanding
B-1.2: Current state of science, models and data
B-1.3: Current provincial capacity
B-1.4: Current Policy, Regulations, and/or Guidelines

The province of British Columbia has leading edge climate scientists and researchers studying the effects of climate change. Similarly, leading flood risk assessment practitioners also call British Columbia home. However, a gap remains between the knowledge and needs of flood hazard practitioners and information produced by climate scientists, although this gap is slowly closing as flood impact methods and models that apply future climate projections emerge. Similarly, flood hazard practitioners in B.C. are actively transitioning from a general understanding of the impacts of climate change to specific applications using downscaled climate data to develop robust impact models. In addition, evolving flood-specific climate science results are allowing flood hazard practitioners to move from relatively ad hoc climate change/flood hazard assessments to more detailed data-driven modelling. Although positive examples of this ongoing knowledge expansion can be found, there continues to be a need for broader sharing of this knowledge amongst the climate science community, flood hazard practitioners, key stakeholders, and the Province to ensure broad-based understanding and to ensure adoption that key climate change principles are effectively incorporated into provincial flood hazard and risk assessments.

A key finding of this study relates to the need for industry and/or the Province to commission built for purpose climate data for practitioners. Down-scaled climate datasets are required to align with identified needs for specific purposes to accurately capture targeted responses such as snow accumulation and melt related to freshet flooding, short-duration rainfall related to pluvial flooding, and wind and pressure fields to understanding coastal flooding. Development of these datasets straddles the gap between climate science and flood hazard practitioners; climate scientists need to know exactly what flood hazard practitioners need to drive impact models, and flood hazard practitioners need to understand limitations, uncertainties and availability of new and novel climate model-derived data for the specific project needs. There needs to be improved integration and mutual understanding between these two bodies of knowledge.

To develop an effective integrated province-wide understanding of climate science and impact modelling, the Province needs to develop and maintain leading-edge knowledge and adequate human resources to support flood hazard practitioners, key stakeholders and the public interest. This leadership position can be supported through continuous learning opportunities, expanded staff resources, and increased responsibility and authority related to addressing the impacts of climate change. This understanding, mandate and ownership will help to support programs that are targeted to the needs of users including climate and flow monitoring data collection, climate studies, appropriate downscaling and development of climate datasets, education, and guidance.

At present, the guidance provided to address the impacts of climate change on flood hazards, leans heavily on entities external to the Province including Professional Practice Guidelines and Federal Guidance. Due to the rapidly evolving understanding of climate science and its relationship to flood impact modelling, guidelines can become out-dated very quickly. The current professional practice guidelines “Legislated Flood Assessments in a Changing Climate in BC” (EGBC, 2018) is one example of this. In general, it is incumbent on the water resources professional to understand changing flood drivers and hazards, potentially to a level beyond that reflected in currently available standard guidance.

This study provides improved understanding of the current state of knowledge and application of climate science to flood hazard and risk assessments and how to expand capacity throughout the province and within government. Overall, significant scientific and practitioner knowledge exists within the province, but this expertise must be expanded and coordinated to support understanding amongst the public, private industry, public agencies, and in particular local, regional and First Nation governments who are ultimately responsible for managing flood risk. The Province of BC has an exciting opportunity to provide leadership and oversight for this initiative, to ensure that British Columbia’s communities are resilient to flood hazards, even in the face of a changing climate.

TABLE OF CONTENTS

LIST OF FIGURES

ABBREVIATIONS AND ACRONYMS

AEP - Annual Exceedance Probability
AR - Atmospheric River
BC – British Columbia
BCCAQ - Bias Correction/Constructed Analogues with Quantile Mapping Reordering
CANESM – Canadian Earth System Models
CanRCM4 - Canadian Earth System Model V.2/Canadian Regional Climate Model V.4
CF – Climate and Forecast
CMIP - Coupled Model Intercomparison Project
CMIP5 - Coupled Model Intercomparison Project 5
CMIP6 - Coupled Model Intercomparison Project 6
CORDEX – Coordinated Regional Climate Downscaling Experiment
CRD – Capital Regional District
CSA – Canadian Standards Association
ECCC – Environment and Climate Change Canada
ENV – Ministry of Environment and Climate Change Strategy
ESM – Earth System Model
EWE – Estimated Wave Effect
EGBC – Engineers & Geoscientists British Columbia
FB - Freeboard
FBC – Fraser Basin Council
FCL - Flood Construction Level
FLNRORD – Ministry of Forests, Lands and Natural Resource Operations and Rural Development
GCM – Global Climate Models
GRIB - General Regularly distributed Information in Binary form
GSC – Geodetic Survey of Canada
HDF - Hierarchical Data Format
HHWLT – Higher High Water Large Tide
IAM - Integrated Assessment Model
IDF – Intensity-Duration-Frequency
IDF-CC - Intensity-Duration-Frequency Climate Change Tool
IPCC AR5 - Intergovernmental Panel on Climate Change – Assessment Report 5
MoTI – Ministry of Transportation and Infrastructure
netCDF – Network Common Data Form
NHC – Northwest Hydraulic Consultants
NRCan - Natural Resources Canada
OpenDAP - Open-source Project for a Network Data Access Protocol
PCIC - Pacific Climate Impacts Consortium
PNWNAmet - PCIC NorthWest North America meteorological
RCP – Representative Concentration Pathway
RFC – River Forecast Centre
RHBN – Reference Hydrometric Basin Network
RSLR – Relative Sea Level Rise

SFU – Simon Fraser University
SME – Subject Matter Expert
SS – Storm Surge
TARA - Transportation Assets Risk Assessment
UBC – University of British Columbia
UK – United Kingdom
UNBC – University of Northern British Columbia
UVic – University of Victoria
VIC-GL - Variable Infiltration Capacity Model

PREAMBLE

About this Initiative

Many communities in BC are working to better manage their river and coastal flood risks through a wide range of flood management activities. But current approaches to managing flooding are not always efficient, coordinated, equitable, or cost-effective.

The **Investigations in Support of Flood Strategy Development in British Columbia** is a province-wide initiative aimed at developing a comprehensive understanding of current challenges and opportunities relating to flood management across BC. The focus is primarily on riverine, coastal, and ice jam floods, although other types of flooding are recognized where appropriate. This initiative recognizes that flood management is a multi-faceted, ongoing process requiring the coordination of many organizations, agencies, and orders of government and linked with broader processes, including climate change adaptation and disaster risk reduction, among others.

The BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development retained the Fraser Basin Council to manage and coordinate research and engagement across a broad range of flood management issues relating to governance, hazard and risk management, forecasting, and emergency response and recovery. Consulting teams were retained to undertake research and technical analysis with input from experts, practitioners, and stakeholders from all four orders of government, the private sector, and other organizations. Each investigation produced recommendations to inform flood management program improvements at multiple scales and across many jurisdictions.

Investigations were undertaken across 11 interrelated issues under 4 themes:

Theme A – Governance		
A-1	**Flood Risk Governance**	Review current governance and delivery of flood management activities in BC involving all four orders of government and non-government entities, identify challenges, and recommend changes to improve coordination, collaboration, and overall effectiveness.

Theme B – Flood Hazard and Risk Management		
B-1	**Impacts of Climate Change**	Investigate the state of climate change information and new and existing tools that can support authorities in integrating climate change impacts in flood management.
B-2	**Flood Hazard Information**	Examine the state of flood mapping and dike deficiency information and recommend ways to fill current gaps in flood mapping and manage and maintain information about flood hazards and dike deficiencies.
B-3	**Flood Risk Assessment**	Explore approaches to completing flood risk assessments at various scales, methods for prioritizing risk reduction actions, and standards-versus risk-based approach to flood management.
B-4	**Flood Planning**	Examine the ability of local authorities to undertake integrated flood management planning and opportunities to improve capacity.

B-5	**Structural Flood Management Approaches**	Assess the potential for improvements to dike management, improve the capacity of diking authorities, and implement innovative structural flood risk reduction measures.
B-6	**Non-Structural Flood Management Approaches**	Investigate current and alternative approaches to managing development in floodplains and opportunities for implementing non-structural flood risk reduction actions.

Theme C – Flood Forecasting, Emergency Response and Recovery		
C-1	**River and Flood Forecasting Services**	Identify opportunities to address gaps in the province's hydrometric and snow survey networks and flood forecasting services.
C-2	**Emergency Response**	Investigate roles, plans, and capabilities for flood response and opportunities for improving emergency response.
C-3	**Flood Recovery**	Examine approaches that would support recovery efforts and help reduce future flood risk.

Theme D – Resources and Funding		
D-1	**Resources and Funding**	Investigate resource and funding needs associated with actions to strengthen flood management and evidence in support of proactive flood mitigation.

1 FLOODING AND CLIMATE CHANGE IN B.C.

1.1 Introduction

Issue B-1: Impacts of Climate Change supports improved integration of climate change considerations into flood planning in B.C. This investigation assesses the current state, capacity, and approaches to assess the most prominent flood hazards that are, or could be, impacted by a changing climate, namely:

1. **Riverine flooding caused by spring freshet**
2. **Riverine flooding caused by atmospheric rivers**
3. **Riverine flooding caused by ice jams**
4. **Coastal flooding caused by sea level rise and storm surge**
5. **Pluvial flooding caused by intense local precipitation**
6. **Compound event flooding due to a combination of individual flood mechanisms**

We note that a wide range of 'unconventional flood hazards' (EGBC, 2018) can also arise, including tsunamis, debris floods, debris flows, blockages, groundwater flooding, and dam and dike burst. Since changes to these specific hazards are either tied to changes described in the six most prominent flood hazards and/or are not directly tied to climate-impacted conditions, these hazards are not specifically explored within this investigation. Similarly, other non-stationary issues that affect flood likelihood and magnitude but are not related to climatic factors; such as land use changes, flow regulation/alteration, and tectonically derived land motion are not explored.

Within each flood type listed above, the investigations initially focus on the "current state of understanding" and the "current state of science, models, and data" as described below:

B-1.1 Current state of understanding: Investigate the state of climate change science in relation to B.C. flood hazards.
B-1.2 Current state of science, models and data: Identify current sources of information and models used by experts in the province to predict future climate impacts and investigate opportunities for improved predictive modeling. Focus is paid to the key stages of data development to facilitate integration with hydrologic and hydraulic models used for flood hazard assessments. This includes global climate model usage, climate data downscaling and bias correction, and regional-scale impact modelling.

Subsequent sections of this report focus on "Current provincial capacity" and "Current policy, regulations, and/or guidelines" related to each flood type as described below:

B-1.3 Current provincial capacity: Investigate the capacity of responsible authorities and other professionals and practitioners in the province to integrate climate change impacts and scenarios to inform flood planning and management.
B-1.4 Current policy, regulations, and/or guidelines: Investigate the legislative, policy, and regulatory tools available to responsible authorities in all levels of government for integrating climate change impacts in flood planning and management.

These investigations of each flood type are followed by a set of recommendations designed to advance understanding and application of the impacts of climate change to flood hazard assessments. By addressing each of these investigation topics across each flood type, this investigation provides a comprehensive picture of the current knowledge base and capacity with respect to climate change integration into flood hazard assessments and the current uptake (or lack thereof) of this information by responsible authorities. Identified gaps are highlighted where they exist, and lead to specific recommendations. Gaps and associated recommendations are highlighted throughout the report in call-out boxes as shown and summarized in the project recommendations.

GAP
Statement of gap, limitation or deficiency.
RECOMMENDATION
Suggested mitigating action to reduce or eliminate gap, limitation, or deficiency.

Recommendation box format used in this report to highlight gaps and recommended mitigation actions. All recommendations are summarized in Recommendations

Throughout this report the terms "Province" and "province" are used. The former refers to anything pertaining to the government of the Province of British Columbia. The latter refers to geographical boundaries and all entities within the provincial boundaries.

Appendix C of this report describes the Investigation Methods used to complete this investigation. Interviews and outreach were designed to cover a wide range of specialties and areas of expertise. As a result, interviewees spanned a range of qualifications (i.e. P.Eng., M.Sc., Ph.D., M.A.); sectors (i.e. academia, public sector, regulatory, and private sector); and, flood mechanisms (i.e. fluvial, ice jam, coastal, pluvial).

1.2 Background

British Columbia (B.C.) has a diverse landscape including steep mountainous regions, interior plateaus, inland lakes, and low-lying coastal areas. A variety of flood hazards exist across this heterogeneous landscape causing negative economic, social and environmental impacts, and occasionally the unfortunate loss of life. Flooding in the province is driven by a wide range of physical and environmental processes, and takes many forms, including:

- **Riverine floods** occur as streams and rivers rise due to heavy rainfall, rapid snowmelt, and/or ice jamming, and inundate surrounding floodplains.
- **Lacustrine floods** occur as lake levels rise in response to high inflows and inundate low-lying surroundings.
- **Coastal floods** occur as storms and tides combine to produce extreme ocean levels, with the added potential of flooding caused by a tsunami, that can inundate coastal areas.
- **Pluvial floods** occur as heavy, short duration rainfall events exceed the capacity of natural and built landscapes to dissipate storm water.

Flooding in B.C. has occurred throughout history due to natural variability in the climate and Earth systems. Indeed, Indigenous oral history speaks of severe flood events (Ludwin, et al., 2005). Recent historical floods demonstrate many of these flood mechanisms including:

- **Grand Forks, 2018: riverine flood.** Causal factor: spring rain-on-snow event.
- **Prince George, 2007: riverine flood**. Causal factor: ice jam.

- **Squamish, 2003: riverine flood**. Causal factor: record autumn rainfall.
- **Okanagan Valley, 2017: lacustrine flood**. Causal factor: record spring inflows into Okanagan and Kalamalka Lakes.
- **Haida Gwaii, 2003, coastal flood.** Causal factor: storm surge with peak winds over 110 km/h.
- **Lower Mainland, 2020: pluvial flood.** Causal factor: persistent extreme rainfall.
- **Port Alberni, 1964: coastal flood.** Causal factor: earthquake-triggered tsunami.

In these and other cases, flooding was caused by the confluence of extreme and difficult-to-forecast individual weather and climate conditions. Over time, statistical records and flood reoccurrence provide the ability to develop probability estimates of flood events of a given severity or extent occurring at a given location. Annual exceedance probabilities (AEPs) are developed directly from these statistics and play a pivotal role in assessing flood risk across the province (EGBC, 2018).

Global human-caused climate change enters the provincial flood risk equation, because climate change, along with other factors, can alter the environmental conditions that influence flood frequency and magnitude. Significant changes to flood frequency and magnitude are expected to occur over the planning horizon for most infrastructure. Furthermore, this encompasses timeframes where significant land-use modifications and urban and rural expansion will alter the associated flood hazard and risk. As well, other episodic events, such as forest fires and infestations, will temporarily affect the hydrologic response. A key first step to understanding the influence of climate change on floods in B.C. involves an understanding of broad climate trends across the province. This knowledge is critical, since it forms the basis for subsequent, more nuanced investigations of flood mechanism-specific changes that are discussed in this report.

Minimum, maximum, and mean temperatures across the province have increased across almost all seasons, with the greatest seasonal-average increases occurring to winter temperatures in northern regions of the province (Figure 1-1). Precipitation has generally increased across the province as well, with a broad trend towards greater relative increases to the east; changes to seasonal trends are less defined (Figure 1-2). Temperature and precipitation variations drive changes to other aspects of the environment, including snowpack (Figure 1-3) and glaciers (Figure 1-4).

Simultaneously, average sea level has been shifting province-wide, with large differences between regions related to regional increases in ocean height combined with spatially variable changes in vertical land motion (Figure 1-5). The wide variability of broad-scale provincial climate change signals is amplified when considering not just seasonal-average changes, but climate change-driven shifts to extreme conditions that are more directly related to individual flood events.

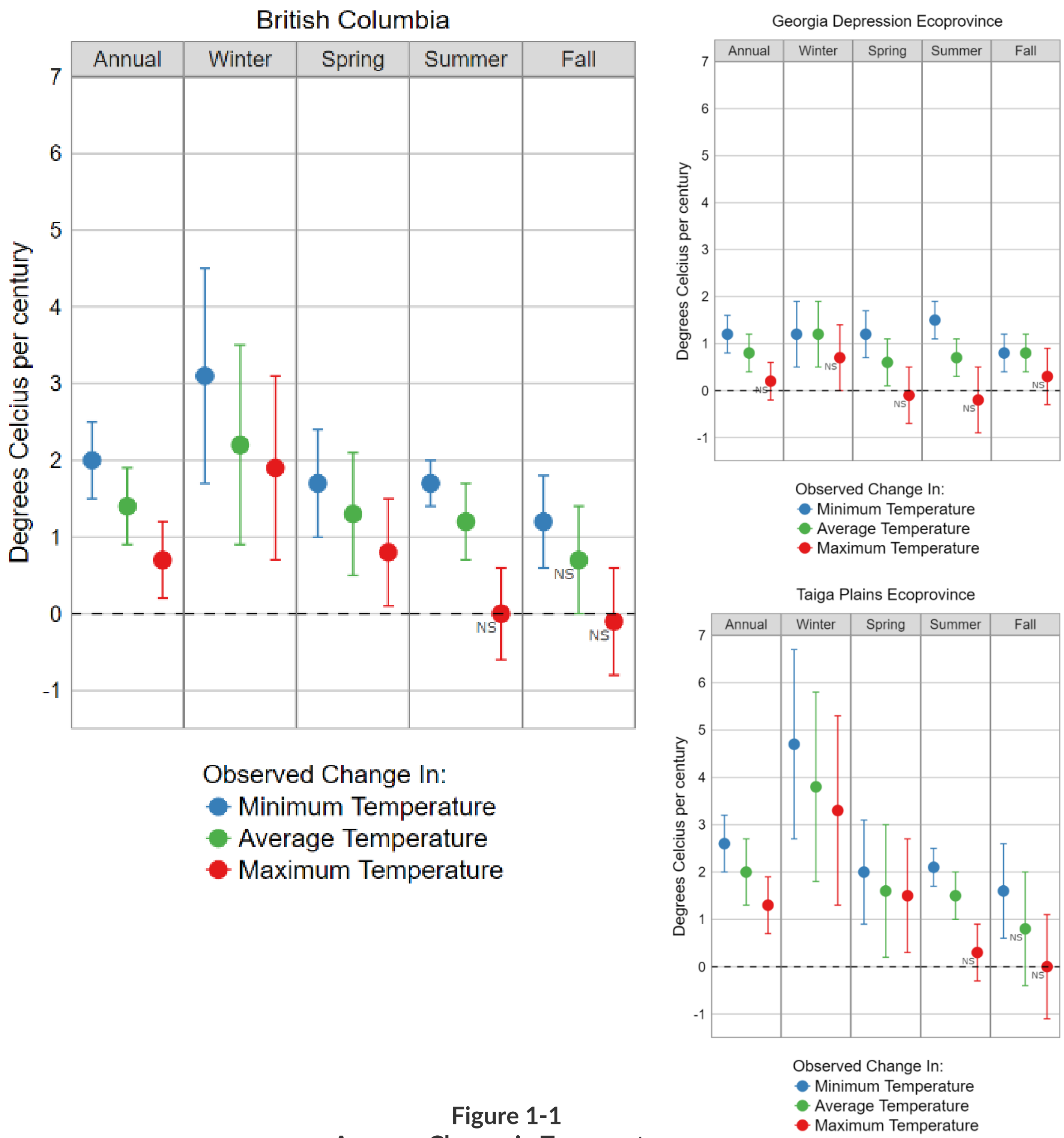


Figure 1-1
Average Change in Temperature

Average changes in temperature between 1900-2013 for entire province (left), and representative southern/northern ecoregions (right top/bottom). (Province of British Columbia, 2020).

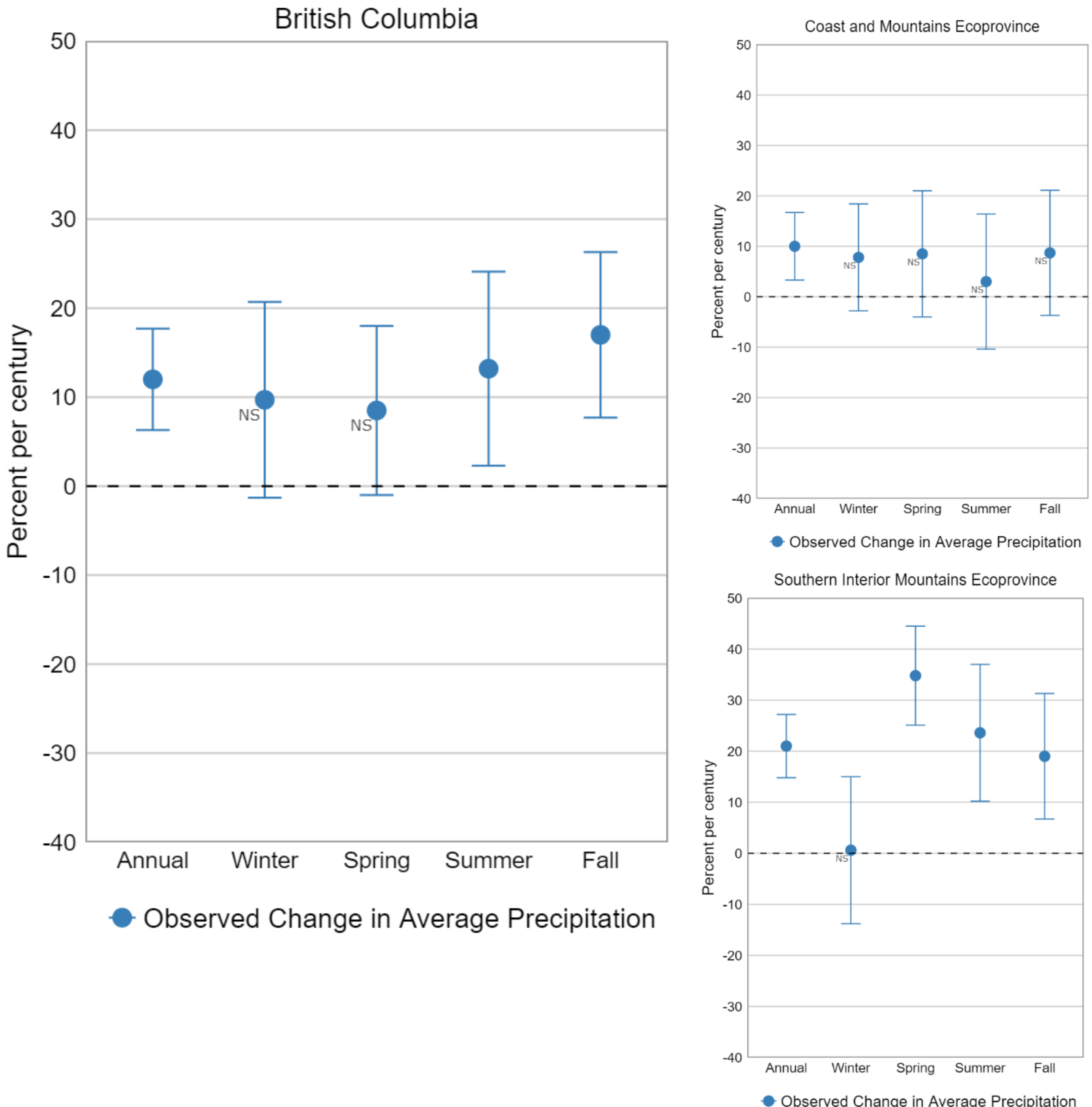


Figure 1-2
Average Relative Changes in Precipitation

Average relative changes in precipitation between 1900 – 2013 for entire province (left), and representative western/eastern ecoregions (right top/bottom). (Province of British Columbia, 2020).

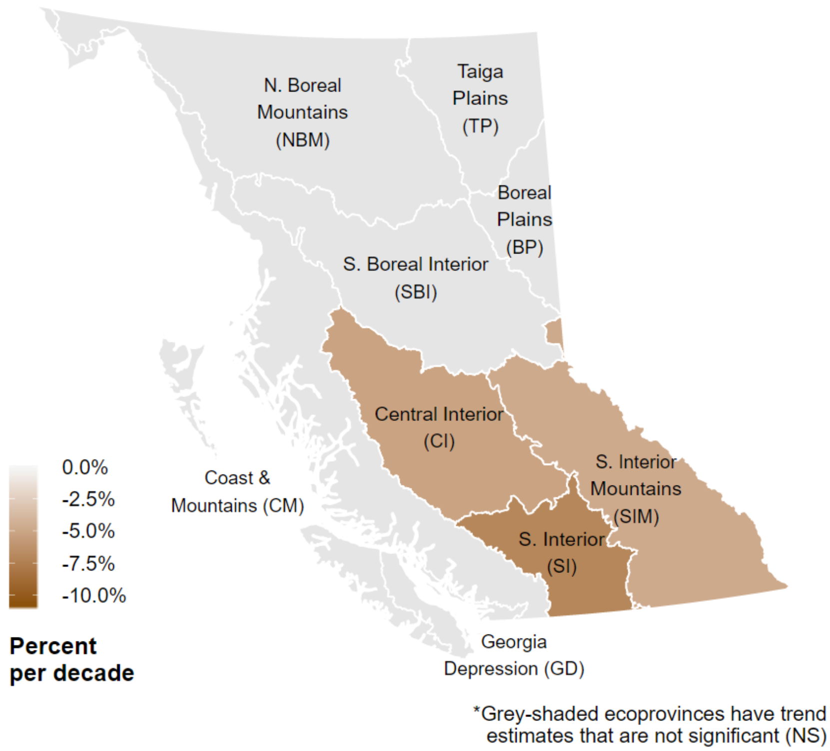


Figure 1-3
Trends in Provincial Snowpack

Trends in provincial snowpack by major ecoregion, 1950-2014.
(Province of British Columbia, 2020).

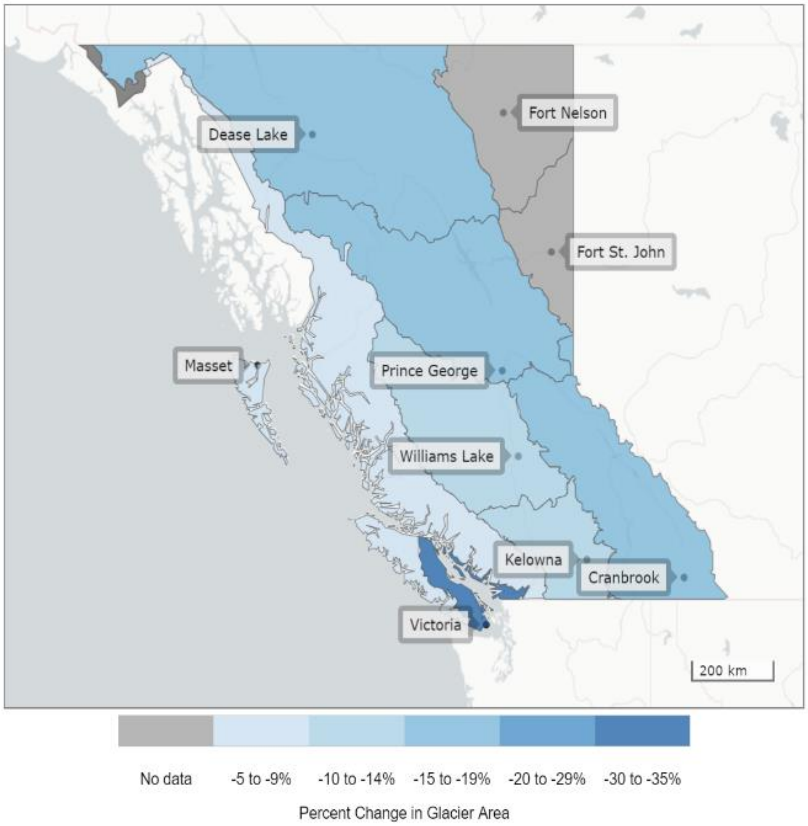


Figure 1-4
Change in Provincial Glacier Area, 1985-2005

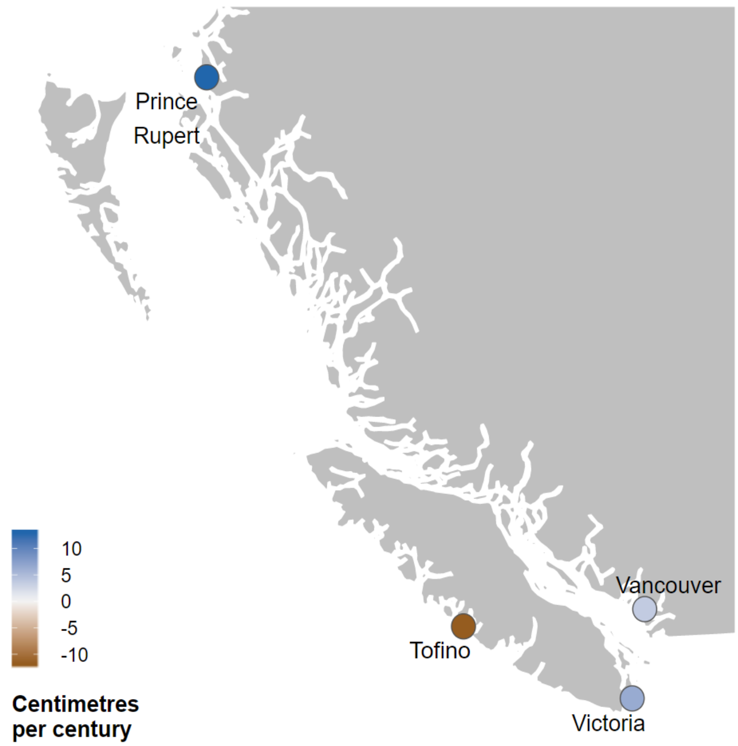


Figure 1-5
Change in Mean Sea Level

Change in mean local sea level for selected directly measured locations in B.C., 1910-2014. (Province of British Columbia, 2020).

Since the climate is changing, the underlying processes that drive flood events are also fundamentally shifting (Khaliq, Report No.: NRC-OCRE-2019-Tr-011, 2019). These hazards will be influenced by climate and weather conditions that have no historical precedent, therefore the historical flow and water level records that have conventionally been used for flood frequency analysis are becoming increasingly unrepresentative for predicting the occurrence of future floods. This means that improving understanding of future floods and the corresponding hydrologic conditions will require increased reliance on modelling that incorporates future climate scenarios, model-based projected response, and model-based hydraulic condition assessments (EGBC, 2018). Suitable methods and acceptable practices that incorporate climate change factors in a consistent manner are not fully developed for completing flood hazard assessments in B.C. This new paradigm for understanding flood risk throughout the province, that relies much more heavily on projection models, introduces new and substantial challenges including:

- Adequate climate change literacy among watershed hydrologists and coastal specialists, including climate change fundamentals and how models are used to predict future events;
- Adequate hydrologic literacy among provincial climate scientists, including understanding of key meteorological and oceanographic data, information and controls influencing provincial flood events and their representation in future climate change impact models;
- Availability of a well-tested, operational model ‘toolchain’, including (but not limited to): climate models, downscaling methods, hydrologic models, coastal oceanographic models, hydraulic models, and climate-change-compatible statistical methods, flood risk methodologies, and flood standards guidance;

- Availability of well-sampled, robustly validated input data to modelling processes, including (but not limited to): hydrometric data across all seasons, meteorological records across a range of elevations and landscapes and hydrologically or oceanographically important locations, and relevant datasets addressing non-stationary issues such as provincial wildfire burnt areas (and future fire risk data), and time-evolving land use data;
- Close integration of climate-enabled flood science/modelling with responsible authorities, industry, and approving agencies.

Addressing these challenges will involve developing acceptable methodologies and best practices that are supported by the professional community, supported by education and training, and guided by policies, guidelines, and regulations. With appropriate tools, resourcing and coordination, Qualified Professionals (EGBC, 2018) will be equipped to address impacts of climate change to provincial flood hazards and risk with best available science for the many types of flood events that can occur throughout the province.

2 RIVERINE FLOODS: SPRING FRESHETS

2.1 Current Understanding

Spring freshets that swell river and lake systems are a major cause of flooding in B.C. Flood risk from spring freshet tend to be more dominant in larger watersheds. Extreme high freshet conditions are often related to a combination of overlapping climatic factors such as high snowpack from the previous winter, frozen ground, springtime warm spells and springtime storm precipitation falling as rain. The 2018 flood in Grand Forks is a recent example of such an occurrence when a rain-on-snow event combined with spring snow melt. Similarly, the 2017 flooding in the Okanagan mainstem lakes resulted from a combination of high elevation snow melt and above-average rainfall.

Figure 2-1
Freshet Driven High Flow Near Cache Creek

Image: Jennifer Ferguson / Facebook

Freshet flood likelihood and magnitude will be influenced by climate change-induced shifts to these flood drivers including end-of-winter snowpack magnitude, spring temperature variations, and precipitation extremes. On their own, these changes may not cause major floods, but the overlapping likelihood of occurrence can lead to extreme events. Projected snowpack changes vary by provincial geography; southern regions are expected to experience less seasonal snow accumulation due to warmer temperatures and an increased proportion of precipitation falling as rain. However, in northern and high elevation regions, increased winter precipitation falling as snow may overcompensate for shoulder-season snow-to-rain transitions. Increasing rain at higher elevations where snow persists will increase the likelihood of flood-inducing rain-on-snow events, while rain-on-snow events at lower elevations will decrease due to loss of snow (Musselman, et al., 2018). This highlights the need to pay increased attention to the range of factors that can drive the flood magnitude including anticipated rainfall, extended cool springs, and rapid temperature increases in addition to the current focus on depth of snowpack. Figure 2-2 shows the distribution of watershed 'types' across

Canada. Overall, climate change will cause an expansion of ‘mixed’ and ‘pluvial-type’ watershed behaviour into the currently nival watershed-dominated interior of B.C.

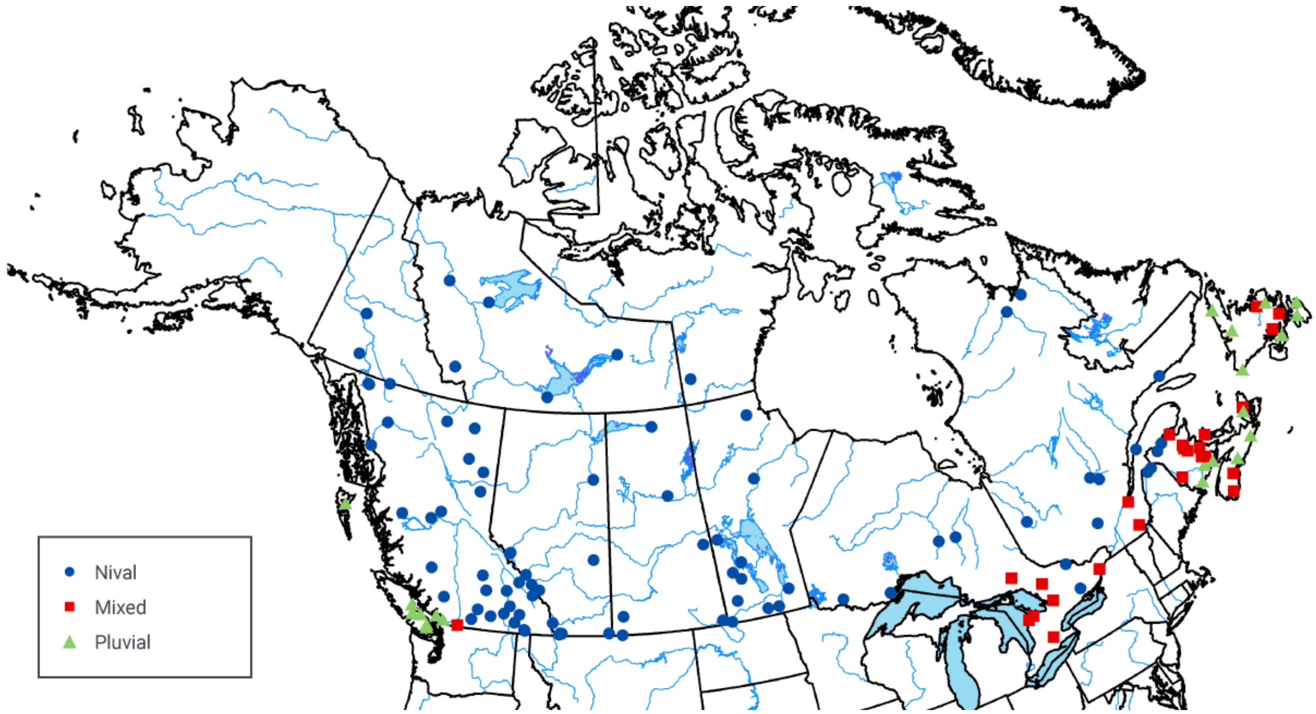


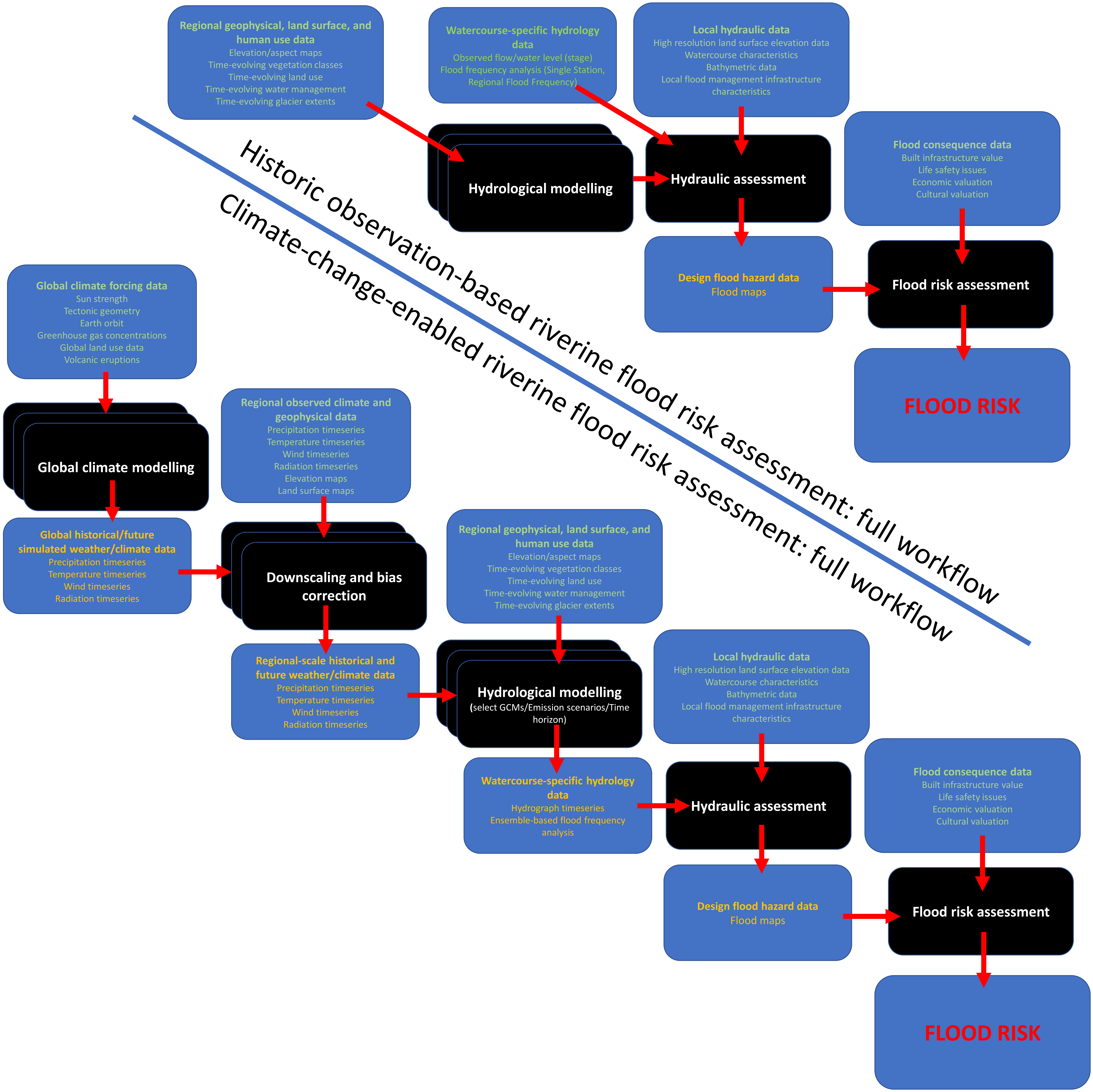
Figure 2-2
Distribution of Watershed ‘Types’ Across Canada, for a Selection Of Well-Studied Watersheds

Image courtesy (Environment and Climate Change Canada, 2019).

2.2 State of Science, Modelling and Data

Since spring freshet flooding is determined by a confluence of separate climate drivers, direct estimates of changes to spring freshet flooding in response to climate change is difficult. This challenge is compounded by the local-scale contributions to watershed-specific responses (Musselman, et al., 2018) that are dependent on elevation-specific hypsometric data. These complications confound simple use of extrapolations of historical conditions, and/or projected shifts in regional climate parameters (e.g., annual or seasonal precipitation or temperature) as direct proxies for shifts in future watercourse-specific flood magnitude. Instead, use of a more complex “toolchain” that spans from global climate models, through downscaling, continuous (i.e., multi-year) hydrologic modelling, to hydraulic assessments, must be employed, to develop estimates of freshet-driven design flow rates and flood levels that take into account a climate change signal (Khaliq, 2020). This toolchain, as shown below, differs substantially from traditional approaches to flood hazard assessments which are based primarily on completing frequency analysis of historical flood records or developing deterministic watershed models. Nonetheless, to understand watershed response to a changing climate, it is critical to employ this more complex methodology as mirrored in emerging national guidance (Khaliq, 2019).

The state of science, modelling and data across this toolchain, as described in Figure 2-3, spans the full workflow for climate change-enabled provincial flood risk assessments.


Regional geophysical, land surface, and human use data
Elevation/aspect maps
Time-evolving vegetation classes
Time-evolving land use
Time-evolving water management
Time-evolving glacier extents
Watercourse-specific hydrology data
Observed flow/water level (stage)
Flood frequency analysis (Single Station, Regional Flood Frequency)
Local hydraulic data
High resolution land surface elevation data
Watercourse characteristics
Bathymetric data
Local flood management infrastructure characteristics
Hydrological modelling
Hydraulic assessment
Flood consequence data
Built infrastructure value
Life safety issues
Economic valuation
Cultural valuation
Design flood hazard data
Flood maps
Flood risk assessment
FLOOD RISK
Historic observation-based riverine flood risk assessment: full workflow
Climate-change-enabled riverine flood risk assessment: full workflow
Global climate forcing data
Sun strength
Tectonic geometry
Earth orbit
Greenhouse gas concentrations
Global land use data
Volcanic eruptions
Global climate modelling
Regional observed climate and geophysical data
Precipitation timeseries
Temperature timeseries
Wind timeseries
Radiation timeseries
Elevation maps
Land surface maps
Global historical/future simulated weather/climate data
Precipitation timeseries
Temperature timeseries
Wind timeseries
Radiation timeseries
Downscaling and bias correction
Regional geophysical, land surface, and human use data
Elevation/aspect maps
Time-evolving vegetation classes
Time-evolving land use
Time-evolving water management
Time-evolving glacier extents
Regional-scale historical and future weather/climate data
Precipitation timeseries
Temperature timeseries
Wind timeseries
Radiation timeseries
Hydrological modelling
(select GCMs/Emission scenarios/Time horizon)
Local hydraulic data
High resolution land surface elevation data
Watercourse characteristics
Bathymetric data
Local flood management infrastructure characteristics
Watercourse-specific hydrology data
Hydrograph timeseries
Ensemble-based flood frequency analysis
Hydraulic assessment
Flood consequence data
Built infrastructure value
Life safety issues
Economic valuation
Cultural valuation
Design flood hazard data
Flood maps
Flood risk assessment
FLOOD RISK

The full workflow shown above provides a thorough and robust approach to undertaking a flood risk assessment. However, in many cases resource limitations, such data availability in remote locations, may make application of the full workflow impractical. In these cases, a less robust flood risk assessment methodology may be warranted. Nevertheless, application of the elements included in the full workflow should be included where possible.

2.2.1 Global Climate Modelling

Global climate models (GCMs) contain both land surface and hydrologic model components, such that common hydrologic variables that influence spring freshet-based flooding, such as winter and spring temperatures, precipitation, snowpack, and gridded runoff, are all direct outputs of some global climate models (Lawrence, et al., 2016). Improvements to these directly simulated elements are progressing rapidly, in line with broader global climate modelling improvements. Coarse global model resolutions and global calibration/tuning means these outputs, which are produced at daily and occasionally sub-daily resolution over historical and future periods, are suitable for continent or global-scale assessments. However, in most cases, direct modelled streamflow outputs from GCMs are, at present, not suitable for direct use at local or regional scales. Instead, the hydrologically relevant meteorological GCM output fields are saved and subsequently downscaled and bias corrected for regional/local scale use. Appendix A provides more detail on climate models, ensembles, downscaling, bias correction and impact modelling.

GAP

Current GCMs are low resolution and direct GCM hydrologic output is not suitable for local or regional scale freshet flood assessments.

RECOMMENDATION

Monitor GCM development for direct hydrology simulations with quality and resolution suitable for regional and local freshet flood assessments.

At present, operational climate modelling output is primarily sourced from the Coupled Model Intercomparison Project 5 (CMIP5) (Arora & Cannon, 2018). The coupled Model Intercomparison Project 6 (CMIP6) GCM simulations (Eyring, et al., 2016), is currently in progress at many global modelling centres, including the Canadian Earth System Model at the Canadian Centre for Climate Modelling and Analysis in Victoria (Swart, et al., 2019). This output data will increasingly supersede CMIP5 climate datasets over the 2021 timeframe (i.e. in time for the United Nations Intergovernmental Panel on Climate Change Assessment Report 6 (Intergovernmental Panel on Climate Change, 2018)). However, CMIP5 GCM output will continue to be applied in an operational setting for several years, accounting for the significant delay between first publication of CMIP results, required downscaling, bias correction, and analysis efforts that are usually necessary to produce derivative data that would be suitable for operational use in provincial flood assessments.

GAP

CMIP5 GCM output is soon to be obsolete and will be superseded by CMIP6 output.

RECOMMENDATION

Monitor CMIP6 progress for GCM model output and related downscaled data for use in hydrologic modelling.

A key recent advancement in climate modelling is the development of coordinated large ensembles of model simulation output. In the context of freshet-dominated riverine flooding, use of such ensembles potentially enables statistically robust time evolving assessments of extreme flow conditions to be made. This is because ensembles, once processed through downscaling, bias correction, and hydrologic modelling, produce multiple equally valid realizations of stream flow for any particular period that just differ in their timing of internal variabilty. This includes the coincidence of compounding extreme winter and spring season conditions that can cause freshet-based flooding. The use of ensembles can provide large sample sizes that can be used to directly calculate time-evolving, empirically-based estimates of freshet flood probabilities for individual historical and future climatological periods, such as standard 30 year climate normal periods (World Meteorological Organization, 2017). Although these approaches are not widely used by industry yet, this is considered a scientifically defensible approach and is expected to gain traction going forward. For this reason, the processes need to be put in place to support wider adoption.

GAP

Lack of application of ensemble-based hydrologic methodologies limits ability to understand changes to future floods.

RECOMMENDATION

Develop Provincial standards for using ensemble-based approaches to calculate future design flood statistics and highlight project examples of where these approaches have been applied successfully.

2.2.2 Downscaling and Bias Correction

Downscaling and bias correction, as described in Appendix A, will play a key role in translating freshet flood-relevant information from coarse and potentially bias-prone GCM output, to finer-scale, observationally constrained regional climate conditions that are suitable input for hydrological models. However, in the context of freshet flood modelling, care needs to be taken with applying and using downscaled and bias-corrected data. In particular:

- Downscaling techniques may still retain overlying climate model biases (e.g. overly warm springtime temperatures). If not appropriately accounted for, these could significantly skew subsequent freshet flood-based results, given that snow melts and the rain/snow transition occur at an absolute temperature threshold around 0° C. This bias could severely skew freshet-based flood assessments. An example of this issue is demonstrated in the recent assessment of Okanagan mainstem lakes by ((NHC), March 2020) in which they applied additional statistical bias correction to dynamically downscaled climate model results, prior to use in the regional hydrologic models.
- Statistical downscaling techniques can generate arbitrarily fine downscaled grids of meteorological data. However, increases in resolution should not be confused with increases in accuracy or realism. Statistical downscaling from global to regional scales is likely to miss fine-scale microclimate gradients that can be very important in the provincial context (e.g. sharp spatial snowpack gradients across interior rainforest ecoregions). Similarly, statistical downscaling cannot regenerate the occurrence of short-duration, highly localized convective precipitation events that may enhance freshet flooding in small watersheds.

- Downscaling and bias corrections are highly dependent on the quality and quantity of historical observations since these observations are used as the basis for developing transfer functions from GCMs to local scale information. Poor/scarce observations thus have a direct impact on the ability to model future freshet flood-driven change. In the B.C. context, a notable deficiency relates to extremely sparse mid-to-high elevation meteorological, snowpack, and hydrological observations, which greatly reduces the robustness of downscaled climate information from GCMs (Shrestha, 2020) that is used for subsequent freshet flood analyses.

GAP

Lack of climate observations in remote/high elevation regions decreases quality of downscaled B.C. climate data.

RECOMMENDATION

Increase the density of remote and mid to high elevation climate monitoring stations and snow courses throughout B.C.

At present, technical training to support downscaling methodologies is limited to specialized post-graduate studies and lacks widespread understanding and expertise within the province. Professional organizations such as the Canadian Society for Hydrological Sciences provides limited support for developing this expertise, but this support is provided in a haphazard manner based on opportunities and current research rather than adhering to a formalized plan.

GAP

Downscaling methods are complex and imperfect. They can introduce subtle but important downscaled data deficiencies.

RECOMMENDATION

Support technical training for hydrologists and flood hazard specialists to better understand downscaling methods and application of downscaled data.

2.2.3 Hydrologic Modelling

Hydrologic modelling capabilities have advanced significantly over recent decades with advances in computational performance. Development of case-specific semi- and fully-distributed hydrologic models to support flood assessments are now more accessible and should define the baseline methodology for complex flood assessments.

Large-scale hydrologic model output datasets exist for select major watersheds within B.C. (e.g. Fraser River, Peace River, Columbia River) that could be used to support flood assessments, where appropriate. The Pacific Climate Impacts Consortium (PCIC) maintains a large-scale gridded Variable Infiltration Capacity (VIC-GL) model for the aforementioned watersheds. Historic and future streamflow, and other hydrologic dataset estimates are generated for key locations across the province by way of coupling the gridded model with an external routing model routine. Model output is available for both historic and future conditions, highlighting the ability of hydrologic modelling to support flood assessments under future climate conditions.

Given the necessity of utilizing future climate projections to appropriately assess potential changes and inherent variability in future streamflow responses to climate changes, hydrologic models provide an effective means to translate climate model output to streamflow change indices. However, it is important that hydrologic models are calibrated against appropriate historic climate datasets developed in a consistent manner as any future climate projection data that are to be used. By calibrating against historic climate model data, rather than direct observational datasets, inherent climate model bias is consistent across calibration and future model periods, and thus removed.

GAP

General hydrologic modelling approaches are often not designed to specifically capture freshet-based flooding.

RECOMMENDATION

Develop Provincial hydrologic modelling approaches that effectively represent freshet-based flooding in a changing climate by potentially building upon existing frameworks such as the River Forecast Centre's (RFC) CLEVER.

GAP

There is a need for climate model datasets used to force hydrologic models.

RECOMMENDATION

Develop and distribute province-wide downscaled climate datasets at daily or sub-daily resolution.

GAP

Hydrologic models calibrated to observed streamflows may not perform well when driven by climate model-derived data.

RECOMMENDATION

Calibrate hydrologic models that are to be used for future projections using historical climate model data, rather than direct observations.

While useful to inform flood risk assessments, developing site-specific or case-specific hydrologic models presents one of the largest uncertainties in the chain of the overall modelling process (i.e., following climate model output) (Khaliq, Report No.: NRC-OCRE-2019-Tr-011, 2019). The largest reason for this is the inherent complexity of flood mechanisms and causes, and the difficulty to well represent these within hydrologic models. For example, rain-on-snow processes are largely not well represented in existing hydrologic modelling frameworks, yet present a large driver of fluvial flood events, particularly in mountainous interior watersheds. As a result, hydrologic models can often misrepresent peak flow events. Furthermore, there remains a disconnect between the required confidence in the representation of extreme climate events in climate model datasets used to force hydrologic models, and their influence on driving flood events within fluvial systems. As climate models advance in future, their ability to predict extreme weather events, as well as small-scale storm events, will likely be improved along with the ability to improve hydrologic modelling results.

3 RIVERINE FLOODS: ATMOSPHERIC RIVERS

3.1 Current Understanding

Atmospheric rivers (ARs) are discrete, long and narrow atmospheric bands extending from tropical ocean areas to mid-latitude coastal locations such as the B.C. coast (Sharma & Dery, 2020). These features have the potential to transport very large amounts of water in short amounts of time. Since ARs tend to bring both extremely wet and warm conditions they are often colloquially termed “Pineapple Express” events on the Pacific Coast (Pinna Sustainability, 2014). Due to prevalent large-scale atmospheric circulation patterns, AR impacts to the province’s West coast and inland regions are very substantial. These impacts are further exacerbated by the prominent north-south alignment of major B.C. mountain ranges including the Coast, Caribou, Monashee, Purcell, Selkirk and Rocky Mountains. These ranges are detrimentally oriented to transform AR flow into orographic precipitation on western, windward, slopes.

Each AR event typically involves day-scale high intensity, persistent precipitation, focussed on a relatively narrow band, in the order of 100s of kilometres. A result of this geometry is that while AR average impacts (e.g. for example over 30-year climatological normal periods) are widespread, individual AR events are relatively focussed, and can potentially cause flooding in one cluster of watersheds, while sparing adjacent watersheds.

Figure 3-1
2003 Highway Bridge Collapse on Rutherford Creek Near Pemberton

This event stemmed from an atmospheric river-based flash flood and resulted in 6 deaths.
Imagine courtesy Pique Newspaper

A recent comprehensive summary of AR contributions to the West Coast of B.C. was produced by Sharma and Dery (2020). (Sharma & Dery, 2020). A parallel work (Sharma & Dery, 2020) examined variability and change to ARs impacting B.C. AR contributions to precipitation are weighted towards the fall and winter seasons, with more than 50% of total precipitation occurring through the September to November time frame in coastal B.C. On average, between 1979-2016, 35 +/- 5 ARs impacted the B.C. and southeastern Alaska coastline. Remarkably, 90% or more of annual daily maximum precipitation events in this same region occurred in conjunction with AR events, including both extreme rainfall events in maritime coastal regions of B.C. and extreme snowfall events in the interior of the province. During this same time period, the frequency of AR landfalls in B.C. and southeastern Alaska increased significantly.

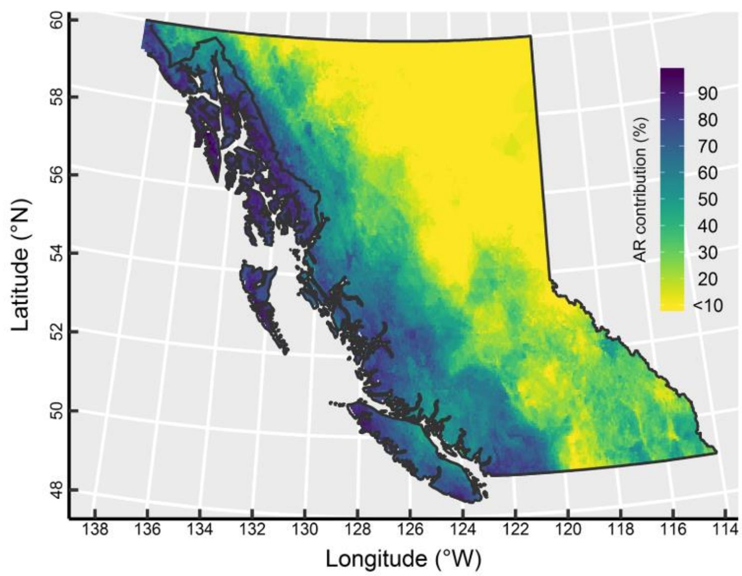


Figure 3-2
Concurrence of Max. Precipitation and AR Events

Percentage of annual daily maximum precipitation events occurring in conjunction with atmospheric river events 1979-2012. Figure courtesy (Sharma & Dery, 2020).

Looking forward, ARs are expected to increase substantially in frequency and intensity on the B.C. coast. The Pinna (2014) report highlights an analysis performed by the Pacific Climate Impacts Consortium, in which a doubling of the frequency of days experiencing AR conditions was projected under the high emission RCP8.5 climate change scenario. Specific to B.C., initial work to summarize climate change impacts to AR-based precipitation was developed by PCIC (Pinna Sustainability, 2014). This work identified an increase in AR precipitation events with warming which is consistent with a more recent global assessment (Espinoza, 2018) that also found similar increases globally. These increases were tied to wider, longer and more intense individual AR events.

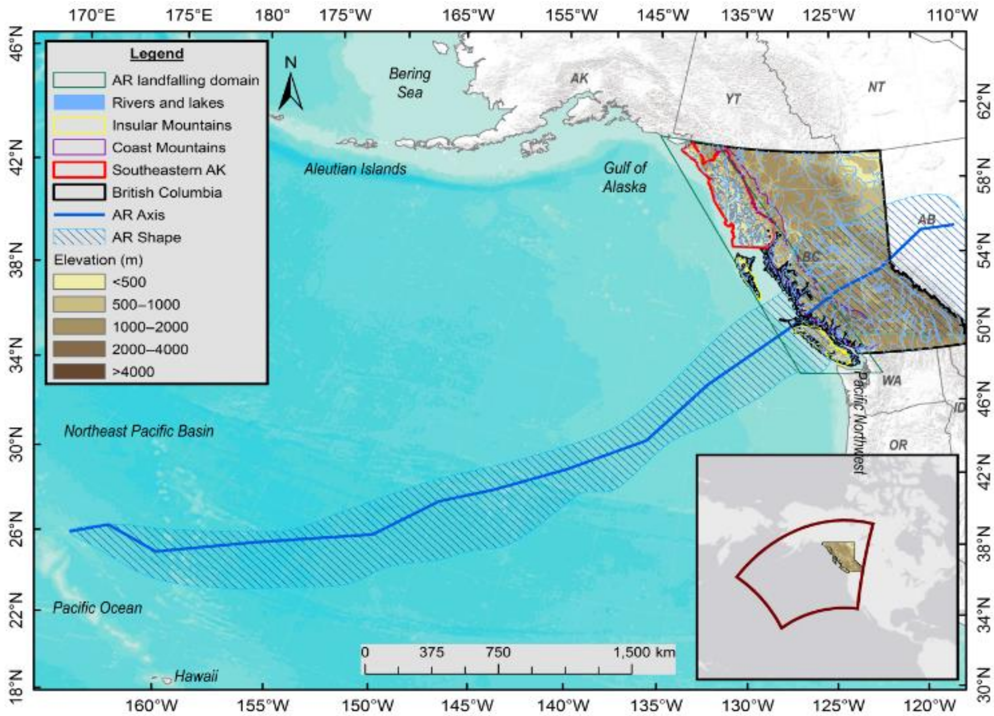


Figure 3-3
October 4, 2014 Atmospheric River Track

Image courtesy (Sharma & Dery, 2020)

The understanding of climate change-influenced effects on ARs and their impacts to B.C. (Pinna Sustainability, 2014) is developing rapidly. A particularly important role of AR changes in influencing riverine flooding in B.C. stems from their sensitivity to phases of precipitation and potentially fundamental impacts on major river flood dynamics. This was highlighted by a recent exploratory analysis by provincial climatologists and hydrologists (Curry, Islam, Zwiers, & Dery, 2019). Using an ensemble of VIC hydrological simulations of the Fraser River Basin forced by national-scale downscaled and bias corrected historical and future climate projection simulations, (Curry, Islam, Zwiers, & Dery, 2019) they identified a potential shift in future Fraser River freshet timing and seasonal magnitude, from entirely spring freshet-based to a case where an increasing fraction of Fraser River peak flows occur in the fall.

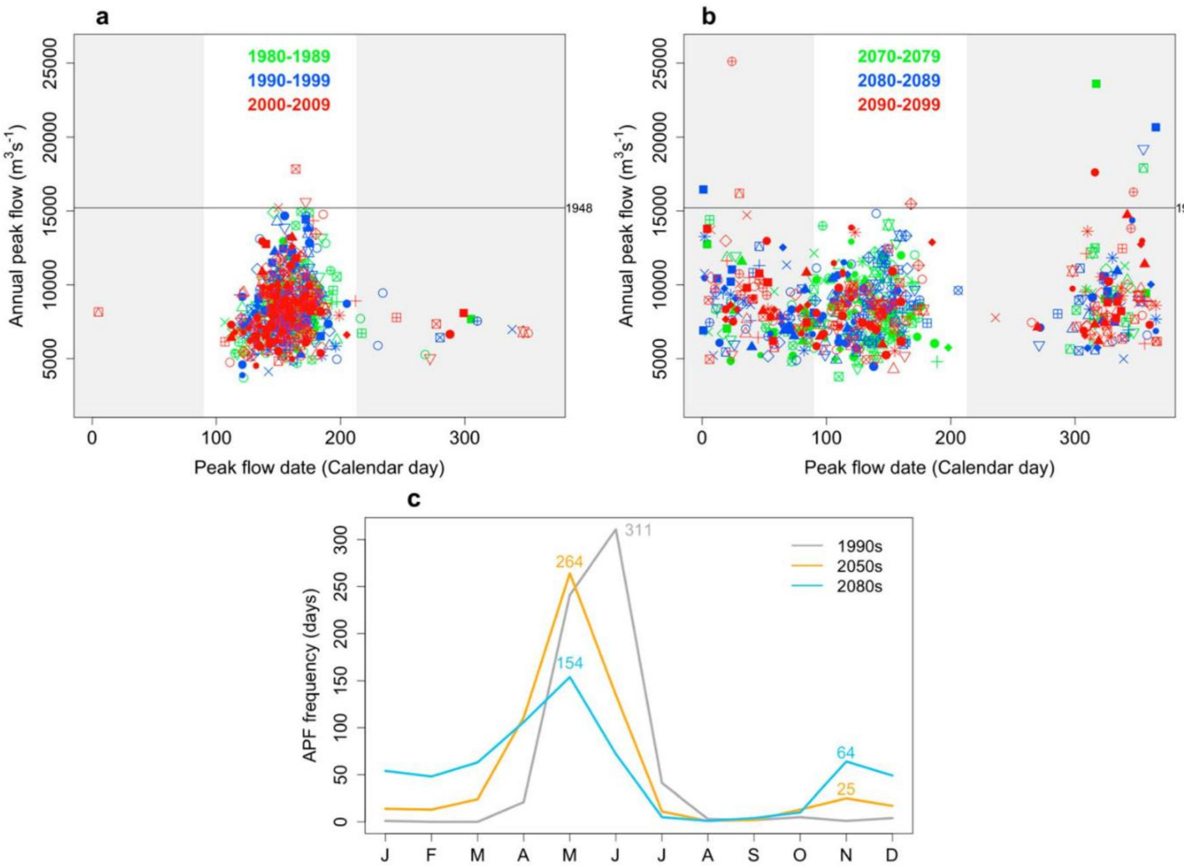


Figure 3-4
Shift in Fraser River Annual Maximum Daily Flood Timing and Magnitude

Note: Shift in Fraser River annual maximum daily flood timing and magnitude between 1980-2009 (a) and 2070-2099 (b) under RCP8.5. (c): frequency hydrograph, indicating number of annual maximum floods detected within model ensemble for each month, for different historical/future periods. Note emergence of significant fall/winter cold season annual maximum flood events. Figure courtesy (Curry, Islam, Zwiers, & Dery, 2019).

This possible change in behaviour of B.C.'s largest Pacific-draining river is closely linked to AR influences. As the climate warms, less cold-season precipitation falls as snow in the Fraser Basin, and rather falls as rain. Thus, instead of contributing to winter snow accumulation and subsequent spring freshet flow, this cold-season rain contributes immediately to cold-season runoff. Concurrently, cold season precipitation due to ARs increases, and cold season runoff attributable to AR events results in more significant Fraser River flows occurring during non-freshet periods. This finding is particularly notable in the context of current use of Fraser River "floods of record" as the basis for large scale Fraser River flood hazard mitigation and flood response planning, as it suggests that historical records of freshet dominated floods are shifting. While this finding is Fraser River-specific, it points to the need for a critical assessment of dominant modes of flooding on other watercourses throughout the province, and their relationship to increasing AR frequency and severity.

3.2 State of Science, Modelling and Data

3.2.1 Global Climate Modelling

AR events impacting western North America have attracted increasing scientific attention, particularly due to their dominant role in producing consequential flooding in coastal areas in the American West Coast states and specifically California. This was epitomized by the 2017 Oroville Dam failure (U.S. Global Change Research Program, 2017). Development of B.C. specific AR-based flood hazard assessments may be able to leverage extensive US-based AR-specific science and modelling advances, such as in "Defining uncertainties through comparison of atmospheric river tracking methods" (Shields, et al., 2019).

ARs are of sufficient size to be reasonably simulated in current global climate model simulations, although small-scale features are lacking (Payne, et al., 2020). This same comprehensive review highlights that climate warming is expected to increase the intensity of individual AR events, due to the ability of a warmer atmosphere to carry more water vapour. On the other hand, climate change will also shift the global pattern of landfalling ARs, and this change, particularly relative to the B.C. coastline, is very poorly constrained with current climate model simulations and studies. Nevertheless, GCM-based projected global changes to AR conditions suggest more frequent, and more severe AR landfalls to B.C., combined with greater AR-driven snow/ice melt due to rain-on-snow events, and consequential flooding events. This understanding will likely improve in direct relation to ongoing improvements to the spatial resolution of GCMs such as the CMIP6 model ensemble, which have been demonstrated to improve representation of ARs.

GAP

The potential growth of atmospheric river-dominated flood peaks due to climate change is poorly understood.

RECOMMENDATION

Support basic research to better constrain the link between climate change, atmospheric rivers, and peak flooding.

3.2.2 Downscaling and Bias Correction

As AR impacts are directly tied (i.e. first order) to precipitation and temperature, it is possible to begin assessing AR impacts to changes in riverine flooding using directly downscaled and bias corrected precipitation and temperature data. This differs from freshet-based riverine flooding, which relies heavily on antecedent seasonal snowpack conditions and thus requires representation of past seasonal climate conditions. Recent successful assessments of historical AR landfall impacts and trends (Sharma & Dery, 2020) were based on data produced by B.C.-based research collaborators (Werner, et al., 2019), indicating that this observational data is useful for assessing the current state of ARs in B.C., and is also likely well-suited to use as the basis for downscaling and bias correction of global model output, prior to AR-focussed provincial hydrological modelling.

Downscaling and bias correction has the potential to improve projections of AR changes affecting B.C. This includes better representation of fine-scale orographic precipitation patterns that resolves whether atmospheric river-based precipitation falls as rain or snow (Curry, Islam, Zwiers, & Dery, 2019).

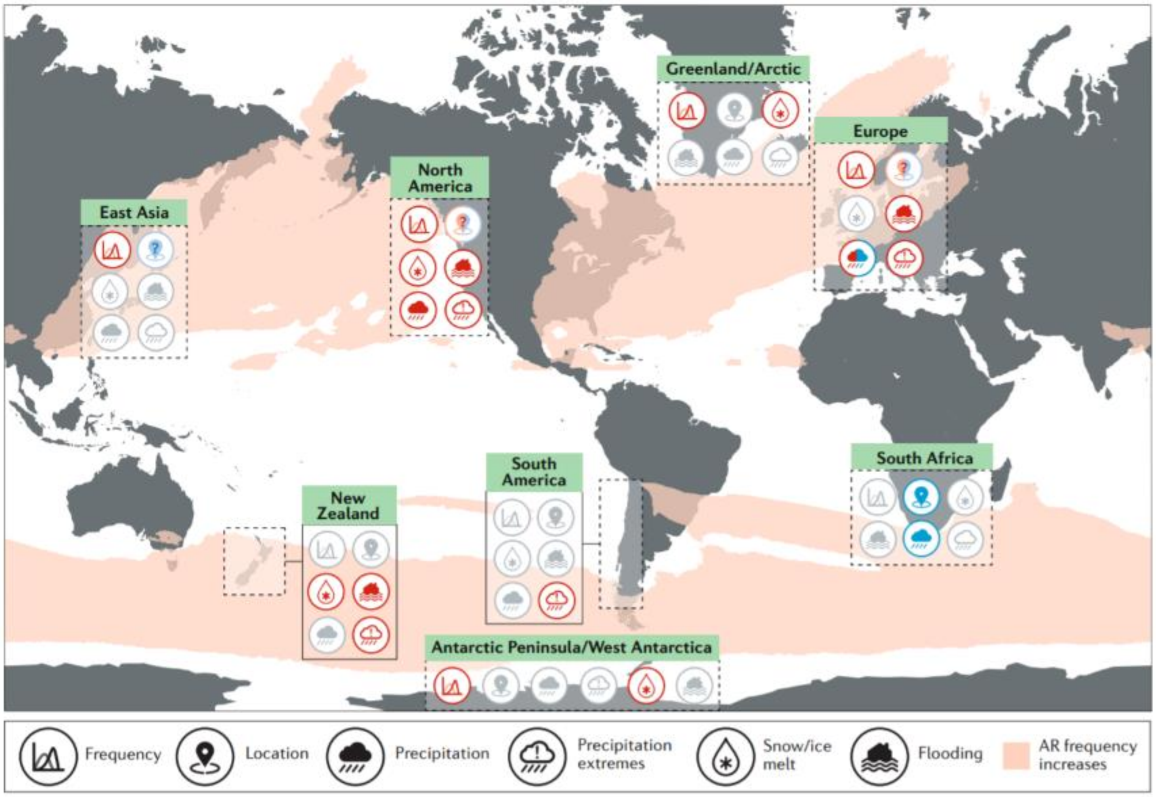


Figure 3-5
Projected Global Changes to Atmospheric Rivers Based on GCM Simulations

Note: The west coast of North America, including B.C., is expected to experience the greatest increase of AR impacts relative to any global location. Figure courtesy (Payne, et al., 2020).

Given the emergence of AR-dominated fall/winter rainfall events as a potentially strong determinant of maximum flood values, comparable in magnitude to freshet driven flooding (Curry, Islam, Zwiers, & Dery, 2019), the recent development of operational multi-variate statistical downscaling techniques, is an important technique to integrate into provincial assessments of climate change-driven AR precipitation change impacts to provincial flooding. B.C.-based researchers are leading state-of-the art investigations such as "Multivariate quantile mapping bias correction: an N-dimensional probability density function transform for climate model simulations of multiple variables, (Cannon, 2018)." These techniques, unlike methods underlying the current generation of statistically downscaled climate information, specifically capture short-term (i.e. daily to weekly scale) relationships between different climate variables that can be critical for assessing real-world impacts. Specifically, in the case of AR-driven cold season flooding (Curry, Islam, Zwiers, & Dery, 2019), the relationship between AR event temperature and precipitation is critical in determining event-specific flooding; colder temperatures could cause the majority of a particular AR event's precipitation over interior plateau regions to fall as snow, thus contributing to springtime freshet flooding. However, warmer temperatures would 'flip' the event-specific precipitation contribution to near-

GAP

Downscaling techniques may impact the ability of downscaled data to represent the full impacts of atmospheric river events.

RECOMMENDATION

Strengthen provincial multivariate statistical downscaling and regional modelling research efforts in support of atmospheric river projections.

instantaneous cold-season flooding. Capturing the relationship between AR event precipitation and temperature via multi-variate statistical downscaling techniques has the potential to resolve this 'flipping' mechanism more consistently.

Use of regional models to produce dynamically downscaled climate data is also an important recent advancement in the context of changes to AR-modulated riverine flooding. This approach typically employs ensembles of regional climate models such as the CORDEX North America multi-model ensemble (Coordinated Regional Climate Downscaling Experiment, 2020), or the Canada-specific coordinated Canadian Earth System Model V.2/Canadian Regional Climate Model V.4 (CanRCM4) Large Ensemble (Environment and Climate Change Canada, 2018). Like statistically downscaled data using multi-variate techniques, dynamically downscaled data has the characteristic of self-consistency between data fields such as temperature and precipitation. For the same reasons as described above for multi-variate downscaled data, this has potentially large advantages when considering climate change impacts to the frequency and/or severity of event-specific AR-based flooding.

3.2.3 Hydrologic Modelling

Despite a closer relationship of AR-driven flooding to immediate meteorological conditions, as compared to freshet-based flooding, AR-driven flood assessments, including those that include a climate change component, likely still require hydrologic models for proper assessment. For example, the impact of a potentially flood-causing AR event in the upper Fraser River watershed to reach the Lower Mainland, many hundreds of kilometres away, is up to a week (Curry, Islam, Zwiers, & Dery, 2019), thus excluding use of Lower Mainland-based, 'real-time' precipitation trends as a suitable measures of Lower Mainland AR-based flooding.

Hydrologic models suitable for assessing AR-specific riverine flooding are similar in nature to those applicable to freshet-based flooding. However, calibration and validation of watershed-specific AR-focussed hydrological models is likely to differ significantly by focussing on model performance in response to cold-season single precipitation events, instead of broader winter conditions and spring-time events. For example, AR-specific hydrologic model design could involve model calibration that is specifically targeted at known AR landfall events, within the broader calibration period.

Recent provincial advances in historical climate data should be targeted as meteorological input for developing AR flood-calibrated hydrological models. Particularly, recent PCIC development of the PNWNAmet (Werner, et al., 2019), that has demonstrated skill in capturing historical ARs (Sharma & Dery, 2020) suggests that soon-to-emerge statistically downscaled data using this same dataset (Shoeneberg, 2020) as an observational target may be well suited for further improving understanding of changes to AR-driven riverine flooding across the province.

GAP

General hydrologic modelling approaches are often not designed to specifically capture atmospheric river-based flooding.

RECOMMENDATION

Develop hydrologic modelling guidelines specifically targeted, calibrated, and validated, to represent atmospheric river-based flooding.

4 RIVERINE FLOODS: ICE JAMS

4.1 Current Understanding

Flooding can occur because of ice jams, particularly as new ice forms and constricts watercourse flow, or as disintegrating river ice is swept downstream during spring freshet and is subsequently trapped by constrictions in the watercourse. The latter case is typically more damaging as it occurs in conjunction with spring freshet. Ice jams potentially account for up to 1/3 of all flood events in Canada (Turcotte, Burrell, & Beltaos, 2019), with ice-induced river floods often exceeding open water flood levels. In the northern parts of other Provinces, 30-50% of floods are attributed to ice-jam flooding, and this may also be the case for the northern interior of B.C. Climate change impacts to ice jam floods are also highly dependent on location-specific climate-regulated river ice characteristics, break-up patterns, and trends in seasonal weather and climate conditions (Turcotte, Burrell, & Beltaos, 2019). The dominance of particular climate change influenced ice jam flood mechanisms must therefore be assessed on a case-by-case basis. For example, some locations that experience a near-total loss of river ice due to warming conditions will naturally also experience a decrease in ice jams. Conversely, increased springtime flows from heightened rain-on-snow events, in the continued presence of substantial river ice, could result in ice jam increases as a dominant response to climate change.

Figure 4-1
Ice Jam in Prince George, 2016

Image from Prince George Citizen

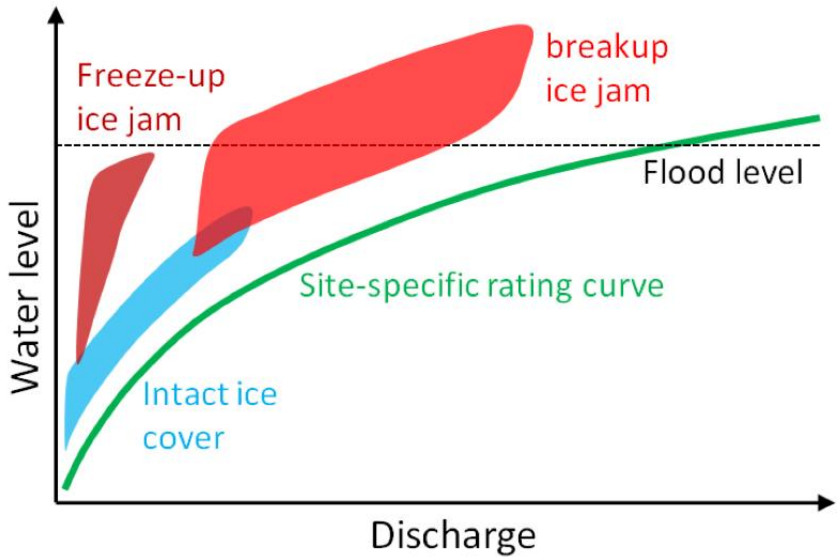


Figure 4-2
Ice Jam-induced Water Levels

Schematic of ice jam-induced water levels, in relation to open water flooding. Ice growth/presence/disintegration significantly increases water levels, compared to standard site-specific rating curves. Figure from (Turcotte, Burrell, & Beltaos, 2019)

The effects of climate change on ice jams are also highly location-dependent (Turcotte, Issue B-1 Interview, 2020), and relate to the local processes that translate regional meteorological signals, into the dynamic response of river ice. Because of this location dependency, multiple pathways from river ice response to climate change are possible as shown in Figure 4-3. These include plausible pathways by which climate change decreases the severity and frequency of ice jam floods, as well as plausible pathways that lead to the opposite result. There are also plausible pathways through which ice jam flooding increases in severity but decreases in frequency, and vice versa. These local-scale impacts, combined with large natural variability in climate conditions responsible for developing ice jams, likely play a large role in the scattered trends in historical ice jam flood magnitudes on unregulated rivers in B.C. (Rokaya, Budhathoki, & Lindenschmidt, 2018).

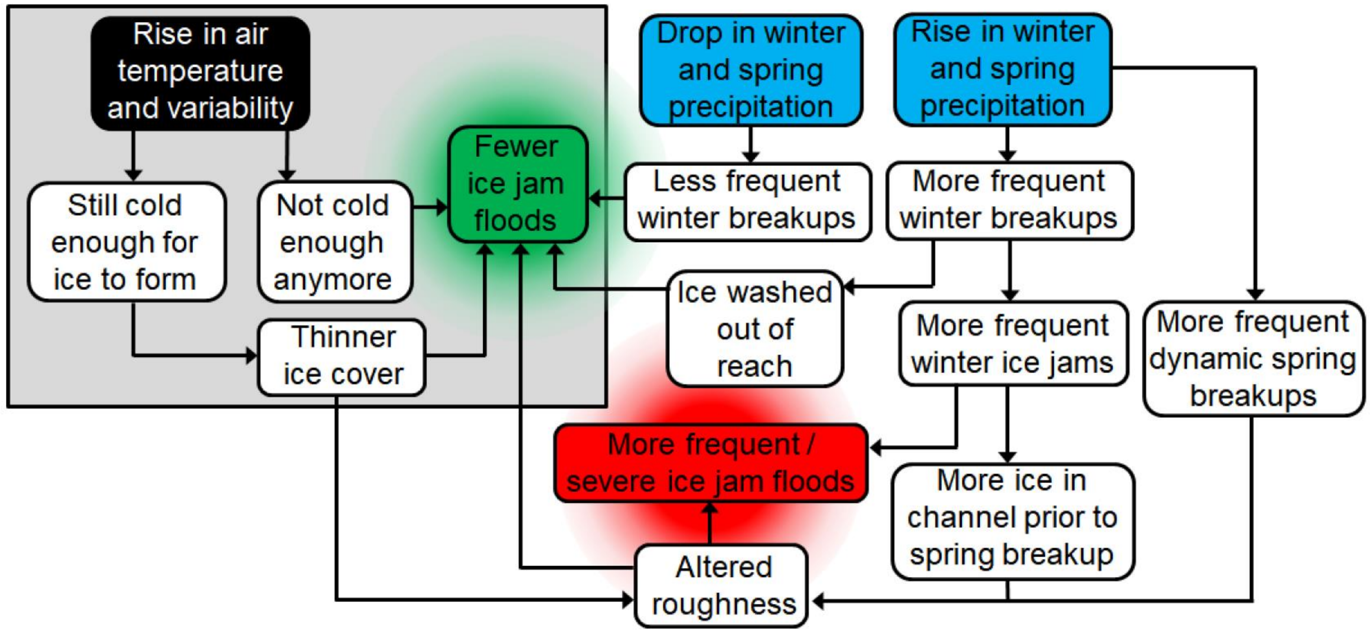


Figure 4-3
Potential Pathways that Climate Change could Directly Impact Ice Jam Flooding

Image courtesy (Turcotte, Burrell, & Beltaos, 2019)

As a result, unlike many other flood hazards, it is unlikely that generalized frameworks to complete location-specific assessments of climate change-driven shifts in ice jam flooding can be made, now or in future. Rather, detailed location-specific investigations that consider both hydrology and hydraulics are necessary.

GAP

Climate change impacts to ice jam flooding cannot be assessed at a broad provincial scale.

RECOMMENDATION

Complete a risk assessment and prioritize development of location-specific assessments of climate change impacts to ice jam flooding.

4.2 State of Science, Modelling and Data

4.2.1 Global Climate Modelling, Downscaling and Bias Correction

Ice jam floods are unmodeled in GCMs, and due to their highly location-specific characteristics, it is unlikely that global climate models will ever directly resolve ice jams in rivers. Additionally, while GCMs are often calibrated and validated with partial respect to overall riverine hydrologic performance, they are not assessed or calibrated with respect to broader conditions directly associated with ice jam flooding. Nonetheless, advances in GCM hydrologic simulations, and/or simulation of hydrologically-relevant meteorological conditions, particularly those related to spring freshet flooding will have a direct bearing on ice jam flooding, because these advances will likely improve important hydrologic inputs to local-scale ice jam flood modelling.

4.2.2 Ice Jam Impact Modelling

Ice jam flooding science involves the intersection of hydrology, hydraulics, solid mechanics, and statistics. As a result, efforts to model ice jams, and climate change influences on ice jams, can be approached from several different avenues (Turcotte, 2020). Given the importance of winter and early spring streamflow in regulating many aspects of ice jam flooding, improved hydrologic modelling of cold-season flows, which are not typically the area of focus, is an important avenue for improvement (Turcotte, 2020). Output from cold-season-calibrated models, run under climate change scenarios, will be important inputs for assessing climate change impacts to ice jam flooding.

GAP

Wintertime observations of river systems are often lacking but are critical for understanding the impacts of climate change on ice jam flooding.

RECOMMENDATION

Increase observations of wintertime hydrologic and meteorological conditions where provincial ice jam flooding occurs.

Beyond hydrologic modelling itself, ice jam assessments require the development of models that represent actual river ice conditions. As river ice is very complex at the local scale, especially as it forms ice jams, approaches to capturing its behaviour range from top-down statistical or empirical representations, to bottom-up mechanics-based models that attempt to explicitly resolve ice dynamics. The top down approaches rely heavily on past relationships between river ice trends and antecedent climate and hydrologic conditions (Turcotte & Morse, River ice breakup forecast and annual risk distribution in a climate change perspective, 2015), whereas the bottom up approaches potentially use large ensembles of computationally intensive simulations to arrive at probabilistic ice jam predictions (Lindenschmidt, Das, Rokaya, & Chu, 2016). It is not clear which method is objectively 'better' at assessing present-day ice jamming (Turcotte, 2020), and equally unclear which method is better suited for assessing climate change impacts to ice jamming. Of the two, it appears that the former approach is experiencing more, albeit limited, use in other Canadian jurisdictions. For example, statistical and empirical methods were used in a trial assessment of climate change impacts to Lower Montmorency River (Quebec) ice jam flooding (Turcotte & Morse, 2015). In this assessment, which built on similar ice jam forecasting frameworks for other river systems, previous break-up events were compared to previous and concurrent climate and hydrologic conditions, to develop a risk rating system that could be applied to current and future climate conditions for specific river reaches.

5 COASTAL FLOODS: SEA LEVEL RISE AND STORM SURGE

5.1 Current Understanding

Coastal floods are the result of extreme sea level events that arise from a combination of high tides, storm surge, wave effects, and relative sea level rise (RSLR). The impacts of climate change to coastal flooding is primarily concerned with RSLR but also considers how changes to "storminess" can impact winds and barometric pressure. The individual components that cause extreme sea levels are combined to define future coastal flood levels. Provincial Flood construction levels (FCLs) using the combined method are based on these design water levels with an additional allowance for freeboard and can be described as follows:

$$FCL = \boldsymbol{RSLR} + HHWLT + \boldsymbol{SS} + \boldsymbol{EWE} + FB$$

Where:

- *FCL=flood construction level*
- *RSLR=relative sea level rise*
- *HHWLT=maximum high tide (calculated as the average of the highest predicted water levels from each year over the previous full 19-year tidal modulation cycle)*
- *SS=total storm surge from a designated (design) storm*
- *EWE=estimated wave effect*
- *FB=freeboard (extra allowance).*

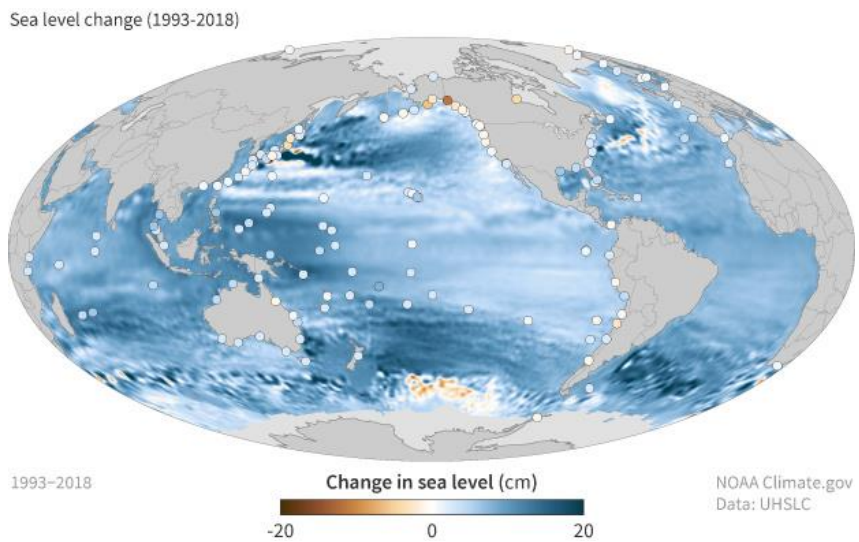


Figure 5-1
Global Pattern of Sea Level Change, 1993-2018

Image: courtesy US National Oceanographic and Atmospheric Administration

Of these terms, RSLR, SS, and EWE, bolded in the above equation, have the most potential to be influenced by climate change. Any climate change impacts on these factors will combine to influence future coastal flood hazard along B.C.'s coastlines. We note that Tsunami considerations have been excluded from the discussion above since they are not directly tied to impacts of climate change excepting that their impact will be exacerbated by increases in sea levels.

Global average eustatic sea levels (i.e. sea level relative to a fixed vertical datum) are rising because of thermal expansion due to warming waters and the melting and increased flow from glaciers, and the large Greenland and Antarctic Ice Sheets (IPCC AR5). Observed global average sea level values mask significant variations in local-scale long-term eustatic sea level changes that arise because of global gravitational field changes related to Greenland and Antarctic mass changes, shifting ocean circulation and heat uptake patterns, and long timescale natural variability (Bornhold, 2008). Most notably, the west coast of North America, including B.C. has, historically, experienced relatively less sea level rise than other coastal regions of the world. While long-term global and regional ocean levels are rising, coastal land elevations are also shifting in a manner that is largely unrelated to climate change (Bornhold, 2008). In B.C., subduction of the Juan de Fuca Plate beneath the North American plate is pushing much of B.C.'s coastline upwards, with periodic drops that can exceed 1 m in elevation during periodic megathrust earthquakes.

Figure 5-2
Storm Driven Coastal Flooding on Vancouver Island

Image courtesy CBC

Glacial rebound also adds to the upward motion of much of the B.C. coast. Conversely, specific areas such as the Fraser Delta are experiencing subsidence due to compression of post-glacial sediment deposits. The combination of regional eustatic sea level and local land elevation changes combine to determine the net 'relative' sea levels in B.C. that affect coastal flooding. Additional components that contribute to the coastal flood hazard include tides, atmospheric pressure and wind effects that contribute to storm surge (The Arlington Group Planning + Architecture Inc., 2013) (Murphy, 2020). Tidal ranges, which are mostly unaffected by climate change, can be large in B.C. (Manson, Couture, & James, 2019) with the prospect of coastal flooding being enhanced during extreme high tides. Atmospheric pressure drops during storm events and longer-term climatic conditions can cause sea level along the B.C. coast to rise by up to 0.5 m (Bornhold, 2008), while concurrent storm-driven waves can cause shoreline run-up heights to increase.

Due to continued global losses of glaciers and ice sheets combined with ocean warming, the trend towards higher relative sea level will continue into the future. The rate of eustatic sea level rise experienced at any point will be highly dependent on global future emission scenarios, as well as on the spatial 'fingerprint' of sea level rise due to loss of particular ice masses. For example, B.C. is particularly vulnerable to ice loss from the West Antarctic Ice Sheet, but less vulnerable to loss from the Greenland Ice Sheet (Kopp, Hay, Little, & Mitrovica, 2015). The level to which B.C.'s coastal flood hazard will be impacted will be further influenced by changes to regional marine storm surge and wave height.

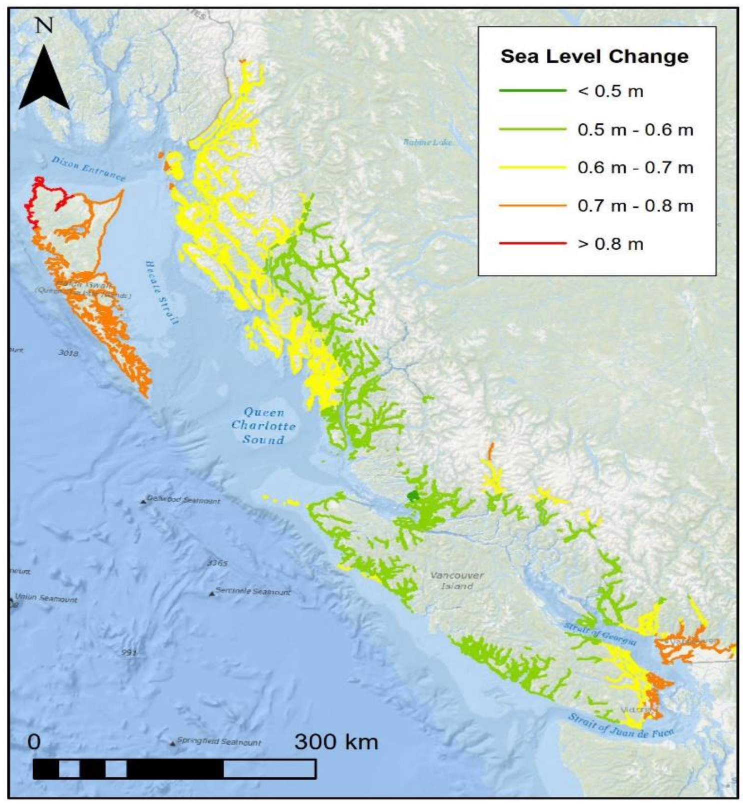


Figure 5-3
Estimated Relative Sea Level Rise Between 2006 and 2099 for British Columbia Coastlines

Data: CanCoast V2.0 database (Manson, Couture, & James, 2019).

Because of these influences, projected relative sea level trends for the remainder of the 21st century vary widely around the country's coastlines. High rates of relative sea level rise and related coastal flooding are expected in regions of the West Coast, most notably in the Fraser River Delta of the Lower Mainland, where continued regional land subsidence will play an important role. Tectonic changes will also play a major role on the B.C. coast, with structural uplift occurring on the west coast of Vancouver Island, particularly Tofino, and subduction occurring in the Strait of Georgia.

Significant uncertainty in sea level rise stems from a variety of sources including poor understanding and projections of changes to the Antarctic Ice Sheet, which altogether holds approximately 65 m of sea level rise potential. Due to this uncertainty, recent estimates of 21st century relative sea level rise for B.C. locations included an additional 65 cm of sea level rise based on the mean of upper end estimates of West Antarctic Ice Sheet mass loss (James & et al., 2014)

5.2 State of Science, Modelling and Data

5.2.1 Global Climate and Land Motion Modelling

Sea level rise in GCMs is presently incompletely represented due to the lack of interactive glacier and ice sheet models within broader GCM frameworks (Fyke, Sergienko, Lofverstrom, Price, & Lenaerts, 2018). This means that sea level rise data from current multi-model GCM ensembles (e.g. CMIP5 and CMIP6) do not directly account for sea level rise from the Greenland or Antarctic ice sheets. These sources on their own have a 7m and 65m of total sea level rise potential, respectively. Instead, indirect means are used to estimate 21st century sea level contributions from these ice masses based on their expected responses to explicitly simulated climate metrics such as global average surface air temperature, and/or standalone studies of Antarctic or Greenland responses carried out external to GCM modelling efforts (United Nations Intergovernmental Panel on Climate Change, 2013). Unfortunately, this approach results in significant uncertainty, with respect to ice sheet and glacier contributions to sea level rise. Coordinated efforts are underway across most modelling centres to improve this basis, including refining observations of ongoing ice sheet, glacier and ocean change (United Nations Intergovernmental Panel on Climate Change, 2019) and establishing ice sheets as part of the simulated Earth system in GCMs (Nowicki, et al., 2016) to directly produce sea level projections. These advances have important implications for updated estimates of global sea level rise, particularly estimates of Antarctic change that are disproportionately important for B.C.'s coastline.

Conversely, estimates of average global sea level rise due to thermal expansion of the Earth's oceans are better understood, as are estimates of regional sea level change due to changing ocean circulation and regional heat uptake patterns (Hu & Bates, 2018). These estimates are directly included in GCM-generated sea level rise projections, including regional variability in sea level changes. Such work is important for B.C.'s coastlines, since regional sea level changes are influenced by global-scale circulation changes.

GAP

Global sea level rise science and projections are developing at a rapid pace that is difficult for Provincial authorities to maintain pace with.

RECOMMENDATION

Regularly monitor developments in sea level rise science and projections from national and international research centres.

The authors acknowledge that establishing sea level rise projections for planning purposes is an arduous process that involves extensive consultation and agreement on the acceptance of risk. Meanwhile, local, regional and First Nation governments desire sea level rise projections that remain consistent over long-scale planning horizons. Setting values that are too conservative has significant financial impacts, especially in seismic prone regions where infrastructure costs are already prohibitive.

Provincial guidance on sea level rise only provides recommended minimum standards in lieu of more site-specific studies. Therefore, local, regional and First Nation governments should be encouraged to complete regional coastal flood hazard assessments for a range of RSLR scenarios to facilitate risk-based approaches and to allow for adaptive management.

Climate change-driven shifts to global storm surges and waves due to climate change are another area of active research; this research is progressing rapidly. Relatively high-resolution model results describing climate change-driven shifts to the magnitude of global coastal flood levels are now emerging (Muis, et al., 2020). However, direct use of data from this global-scale modelling is not yet possible because complexity in B.C.'s coastlines and marine weather systems is insufficiently represented in global-scale models. Instead, regional modelling is still required to assess, at a finer spatial and temporal scale, potential changes to B.C. specific storm surge and waves changes due to climate change.

GAP

Provincial guidance on sea level rise only provides recommended minimum standards in lieu of more site-specific studies.

RECOMMENDATION

Encourage local, regional and First Nation governments to complete regional coastal flood hazard assessments for a range of RSLR scenarios to facilitate risk-based approaches and to allow for adaptive management.

Finally, long-term vertical land motion plays an important regional role in determining B.C. coastal flooding trends. Global models of crustal motion exist but are too coarse to represent important provincial coastal land motion details (James T. , 2020). Thus, more detailed local assessments are necessary.

5.2.2 Regional Sea Level and Surge / Wave Modelling

Assessments of climate-regulated changes to regional relative sea level rise and concurrent surge and wave modelling occurs at scales that are entirely unresolved by GCMs (James T. , 2020). Thus, this information must be obtained through a combination of downscaling, bias correction, and impact modelling at relevant regional scales along B.C.'s complex coastline.

GAP

Provincial coastal planning is not using the most up-to-date assessment of climate change impacts to regional waves and storm surge.

RECOMMENDATION

Adopt emerging, regional datasets of changes to B.C. coastal waves and storm surges such as developed in "Transportation Assets Risk Assessment (TARA) Program" (Transport Canada, 2020) as part of coastal flood planning.

An imminent and significant update to relative sea level rise projections for Canada over the 21st century is expected with the release of the federally-supported national-scale relative sea level product that provides complete coastal coverage of sea level estimates (James, Robin, Henton, & Craymer, in preparation). This dataset significantly supersedes the previous Geological Survey of Canada product (James, et al., 2014), which provided relative sea level rise projections only for sites with vertical land motion measurements. In contrast, data available from "Relative sea-level projections for Canada's coastlines" (James, Robin, Henton, & Craymer, in preparation) estimates relative sea level change at all coastal locations in Canada, including all points on the B.C. coastline. This is achieved via integration of new, nationally-completed crustal velocity estimates (Robin, in preparation) combined with regional sea level change projections developed via CMIP5-based sea level estimates. In this dataset, the contributions from global crustal velocity modelling, which is not appropriate for B.C., (James T. , 2020) is removed and replaced with the nationally-completed crustal velocity estimates. In conjunction with careful assessment of potential dataset deficiencies (e.g., uncertainty around vertical land motion estimates and ice sheet contributions to sea level rise), this new dataset, which practically 'downscales' global sea level projections to a scale relevant to B.C. planning, could be applied as an important input to regional coastal flood planning efforts.

GAP

Provincial coastal planning is not using the most up-to-date national assessment of relative sea level rise.

RECOMMENDATION

Adopt emerging, spatially complete datasets of B.C. relative sea level rise (James, Robin, Henton, & Craymer, in preparation) as part of coastal flood planning.

In addition to local/regional-scale relative sea level rise estimates, local/regional assessments of storm surge and wave changes due to potential changes in storm intensity (i.e. barometric pressure, wind speed/direction) are required to estimate climate change impacts to provincial coastal flooding. Previous estimates of climate change impacts to coastal flooding have largely neglected changes to these factors, potentially related to a lack of a discernable trend in historical storm surge and wave activity (Murphy, 2020). However, dedicated efforts to determine climate impacts to provincial storm surge and waves are now underway. This information should be integrated into provincial coastal flood assessments once available in about 2021 (Murphy, 2020). A prominent example of such an effort is Climate Risk Assessment and Adaptation for Ports and Coastal Infrastructure project, a National Research Council initiative supported by Transport Canada's Transportation Assets Risk Assessment (TARA) Initiative (Transport Canada, 2020). This project, underway at time of this Issue B-1 investigation, is developing high resolution wave and storm surge modelling for B.C.'s coastlines in support of provincial marine transportation infrastructure. Projected wave and storm surge current states and future changes are simulated using 2D storm surge and spectral element wave modelling, driven by hourly historical reanalysis based historical data (European Centre for Medium Range Weather Forecasts, 2020) and daily-scale dynamically downscaled historical and future regional climate model data from a subset of the CORDEX ensemble (Coordinated Regional Climate Downscaling Experiment, 2020). This is disaggregated to sub-daily scales using historical relationships between daily and sub-daily storm and surge events. Information stemming from this effort, expected in about 2021-2022, will include estimates of surge and wave change at about 0.2° resolution for the B.C. coastline, which could be superimposed on improved estimates of provincial relative sea level rise (James, Robin, Henton, & Craymer, in preparation) to significantly improve the accuracy of provincial coastal flooding estimates.

6 PLUVIAL FLOODS: INTENSE RAINFALL

6.1 Current Understanding

Pluvial flooding, or flooding caused by extreme rainfall events, is prevalent in smaller watersheds and urban drainage areas. It can result in significant damage as excess water cannot be routed into natural or manmade drainage systems or absorbed into soils.

Pluvial flood impacts can occur in isolation or concurrent with other flood types, exacerbating the potential flood damage.

Climate change-driven shifts in pluvial flood magnitudes and frequencies are directly related to future changes in short-duration, extreme precipitation events (Environment and Climate Change Canada, 2019). Thus, climate-change caused shifts in pluvial flooding can be reasonably assessed directly from projected changes to extreme rainfall event statistics. This contrasts with other flood types, which often require additional impact modelling to bridge from meteorological climate change metrics to flood response (Khaliq, Report No.: NRC-OCRE-2019-Tr-011, 2019).

Figure 6-1
October Pluvial Flooding, Vancouver

This event was likely related to atmospheric river landfall. Image courtesy Global News.

Engineering analyses of pluvial-based flooding often uses intensity-duration-frequency (IDF) curves (CSA Group, 2018) to quantify extreme precipitation amounts. Consequently, changes to extreme precipitation are often represented in the context of projected IDF curves, or more generally, to changes in the magnitude of annual maximum precipitation events, sampled across a range of sub-daily durations (i.e. hours, minutes). Extreme rainfall intensity across these short duration periods that span all seasons is expected to increase in the future. This is due to a warmer atmosphere which can carry more moisture and thus cause heavier precipitation, along with climate change-driven intensification of individual extreme precipitation events (Li, et al., 2019). Figure 6-2 shows the expected increase in frequency of daily precipitation events extending from the 1986-2005 period to the 2081-2100 period. Daily and sub-daily precipitation values are of most concern to small rainfall dominated watersheds including urban drainage. As a direct consequence of more intense individual rain events, pluvial flooding is expected to increase in B.C. in the future.

Figure 6-2
Shift in Annual Max. Daily Precipitation Events, by Recurrence Time
(RCP8.5 emissions scenario)

Figure courtesy (Environment and Climate Change Canada, 2019)

.

> **GAP**
> **Understanding the impacts of climate change on pluvial flooding is lacking in existing guidance.**
> **RECOMMENDATION**
> **Develop technical guidance for practitioners, on understanding the full spectrum of pluvial events from convective storms to atmospheric rivers.**

Climate change-driven increases in pluvial flooding will largely stem from two primary mechanisms: increased summertime convective storm activity and increased fall/winter atmospheric river frequency and intensity. Because the processes and spatial impacts of these two drivers differ substantially, integration of climate change into pluvial flood planning should assess which factor is more important, on a location-by-location and season-by-season basis. In B.C., coastal locations are typically more susceptible to fall/winter atmospheric river-based pluvial flooding given their windward location with respect to land-falling atmospheric rivers and marine climate which commonly permits fall/winter precipitation to fall as rain. In addition, coastal locations are also prone to strong summertime convective precipitation events. In contrast, interior/eastern regions of B.C. are less susceptible to pluvial flooding from atmospheric rivers, relative to the substantial pluvial flood risk from summertime convective storms.

Climate change-driven intensification of atmospheric rivers as discussed previously in the context of riverine flooding, applies equally to pluvial-based flooding. The magnitude to which summertime convective storms will intensify is still a matter of active and intense scientific research. This primarily stems from the fact that these storm events are relatively small and short-lived; as such they are not represented in current global-scale modelling and likely only partially represented in regional dynamical downscaling. In lieu of explicit representation of these events in future condition modelling, estimates of change to local, short-duration convective storms are instead approximated based on projections of 'proxy' conditions, such as larger-scale atmospheric conditions and changes to daily or multi-day precipitation extreme events (Environment and Climate Change Canada, 2019). The relative importance of storm duration and its impact on flood hazard relates to the unique characteristics of every watershed. For example, the critical storm event for a small, steep urbanized watershed in the province's interior would most likely be a short-duration convective storm whereas the critical storm event for a larger, relatively low gradient watershed in a coastal area would almost certainly be governed by a long-duration storm originating over the Pacific Ocean, and specifically an AR event. However, for many B.C. watersheds the critical pluvial storm event would be unknown; therefore, both AR storms and convective events would need to be considered as part of future condition assessments.

Figure 6-3
June Convective Storm Activity With Potential for Pluvial Flooding, Kamloops, B.C.

Image courtesy Murray Foubister/Flickr

6.2 State of Science, Modelling and Data

6.2.1 Global Climate Modelling

Due to their size and duration, current global climate models are marginally able to directly simulate atmospheric river events. As a result, studies investigating changes to ARs due to climate change are now emerging, and results from these studies have immediate potential to inform provincial projections of atmospheric river changes.

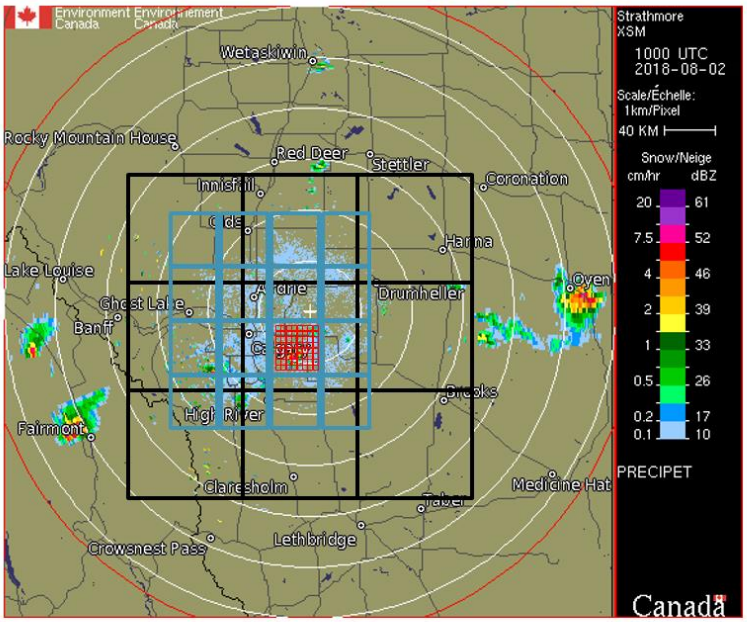


Figure 6-4
GCM Model Resolution Example

Global model (black boxes), operational regional model (blue boxes), and current state-of-the-art regional model (red boxes) resolutions, superimposed on a weather radar image of a damaging 2018 convective storm over Calgary, Alberta. Only state-of-the-art regional model resolution (red boxes) would be able to resolve convective storm details for this type of storm.

In contrast, current GCMs are not able to directly resolve convective storm events, due to the low resolution of these models compared to the relatively small size and short duration of pluvial flood-causing convective storms. Instead, GCMs rely on parameterizations to estimate the net changes of convective storms due to climate change which introduces uncertainty into any extreme precipitation projections that rely on GCM-based input.

GAP

High resolution regional climate modelling of B.C. in support of climate change impacts to extreme precipitation and pluvial flood analyses is lacking.

RECOMMENDATION

Develop operational high-resolution regional climate models of B.C. to better understand climate change impacts to extreme precipitation and pluvial floods.

6.2.2 Downscaling and Bias Correction

Future projections of atmospheric river and convective storms can both benefit from statistical and/or dynamic downscaling. However, the differing natures of these pluvial flood-causing processes require different downscaling and bias correction considerations.

The impact of atmospheric rivers on precipitation across B.C. is in principle captured by currently available statistically downscaled and bias-corrected data products using the BCCAQ downscaling technique (Shoeneberg, 2020). This comes with the caveat that multi-day atmospheric river events simulated by climate models are effectively ‘scrambled’ in time by the downscaling, so that the multi-day signature of these events is lost in the downscaling. This may have important implications for pluvial flood assessments where multi-day, persistent rainfall is of primary concern. In these cases, downscaled data must be used with care, recognizing that multi-day records of persistent rainfall in this data may not be reliable. Dynamical downscaling avoids this problem by explicitly simulating atmospheric river impacts. However, biases in regional downscaled future data can still be inherited from the original GCM simulations, and subsequent statistical downscaling to fix this could still introduce problems as described above. Finally, temperature is important for cold-season atmospheric river-based pluvial flooding; below freezing temperatures potentially avoids damaging pluvial flooding, with the consequent increase in snowpack and potential for subsequent freshet flooding. To this end, multivariate downscaling techniques should be monitored in the next 1-5 years for potential operational deployment of atmospheric river-caused pluvial flood projections (Shoeneberg, 2020). These techniques have the potential to more consistently represent combined temperature and precipitation during atmospheric river events.

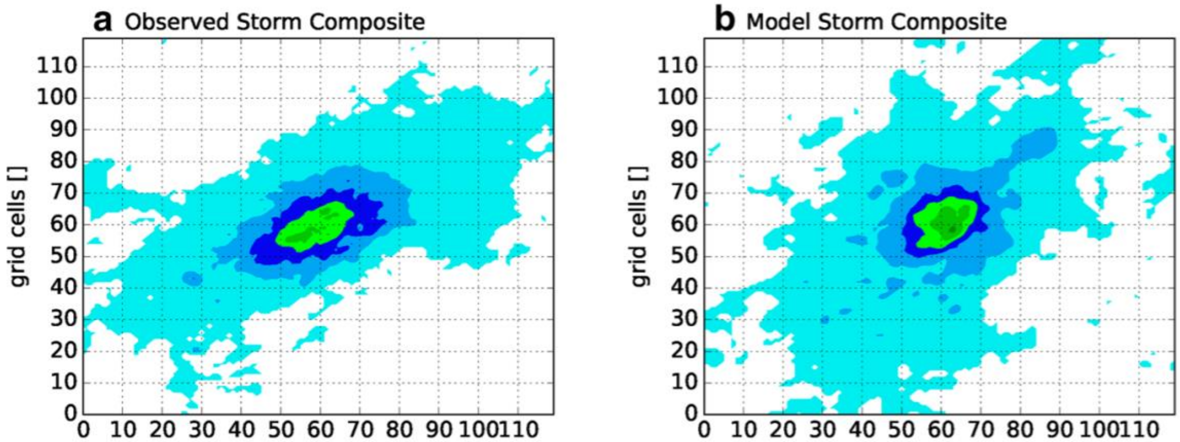


Figure 6-5
Comparison Between Observed and Model-Simulated Storms
(Extracted from a North America-wide
regional model simulation)

Image: (Prein, 2020)

Downscaling of summertime convective storm precipitation events using statistical downscaling and bias correction techniques provides substantial benefits over direct use of GCM data. However, as with atmospheric rivers, care must be taken with using statistically downscaled data to assess future changes to pluvial flooding from convective storm events. GCM input to statistical downscaling has no representation of convective storm events, weakening the statistical basis for using this information to project shifts to these events based on GCM-simulated future change. This is one basis for arguments against blind use of existing, statistically motivated tools such as the IDF-CC calculator. (Simonovic, Schardong, Gaur, & Sandink, 2020)). Instead, increasing attention is being paid to so-called 'Clausius-Clapeyron' scaling approaches, that augment the strong relationship between overall precipitation and warming, with duration and return period specific considerations that cause deviations from pure temperature/precipitation scaling (Li, et al., 2019) (Cannon, 2020). At the same time, extremely high-resolution regional model simulations, often carried out on very large supercomputers at significant expense, are now beginning to resolve individual convective events (as shown in Figure 6-5) and shifts to their frequency and magnitude due to climate change. This research and development progress, which is evolving rapidly, has the potential to significantly improve provincial-scale assessments of pluvial flooding in coming years, as such simulations are increasingly performed to inform flood and climate change decision making.

7 COMPOUND EVENT FLOODING

7.1 Current Understanding

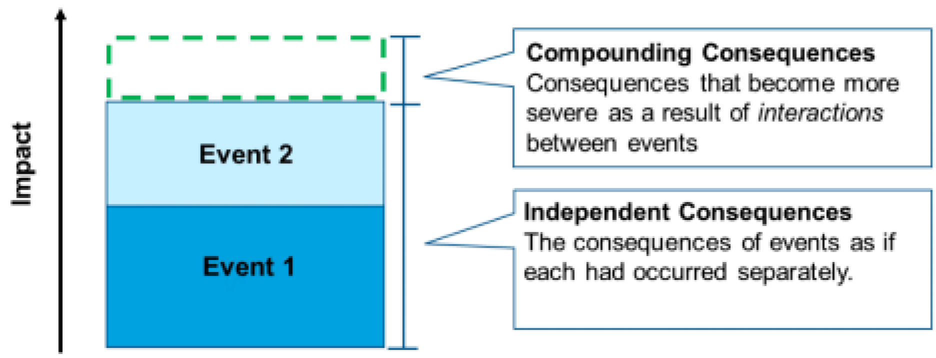


Figure 7-1
Interation Between Compounding Events

Figure indicates the potential for consequences in excess of the simple 'addition' of singular events. Image courtesy (Ministry of Environment and Climate Change Strategy, 2019).

Compound climate events are particularly impactful events that arise from a combination of physical processes occurring at once (Zscheischler, et al., 2018). The magnitude of such events has the potential to far outstrip the size of individual events. Furthermore, the individual event contributions can be magnified through specific combinations. In contrast, the likelihood of extreme event combinations can be very low. Despite this low likelihood, their potentially very high magnitude requires their consideration as part of overall climate risk strategies (Ministry of Environment and Climate Change Strategy, 2019).

Compound events are very important in the context of B.C.-specific flood mechanisms. For example, extreme spring freshet flooding is exacerbated when a combination of high snowpack late into the spring, an extended period of heavy spring rainfall, and warm weather occurs simultaneously. This combination of events led to the recent 2018 Grand Forks flooding. Coastal flooding can also be worsened by compound events such as the combined effects of tide, storm surge, high river flows combined with sea level rise. Given the potential for a shift towards cold-season floods, this type of compound event is particularly concerning, yet in many cases may have no historical precedent.

GAP

There is no comprehensive guidance to evaluate the impacts of climate change as they relate to compound flood events.

RECOMMENDATION

Develop spatial/temporal patterns of flood types under present/future climate conditions and assess overlap regions where compound event flooding may increase in future.

Emergence of rare, difficult-to-predict, but highly consequential compound events that may exacerbate flooding in B.C. can be envisaged using 'storytelling techniques' (Hazeleger, et al., 2015). These events can highlight potential regional-scale compounding mechanisms, that could be quantitatively explored using 'worst-case' sensitivity assessments, to determine effects. Examples in the context of B.C. flooding include the following scenarios:

- **Freshet flooding:** Exploration of the scenario where wildfire causes development of hydrophobic soil prior to winter, a high snowfall over the winter, late freshet, and an extreme spring rain on snow event (MacLatchy, 2020).
- **Atmospheric river flooding:** Exploration of the case where an atmospheric river event coincides with a ripe snowpack, and abnormally high winter temperatures (Curry, Islam, Zwiers, & Dery, 2019).

- **Ice jam flooding:** Exploration of a scenario where a thinner wintertime ice cover combines with increased winter flows to cause more frequent mid-winter ice break-up/ice-jamming cycles (Turcotte, Burrell, & Beltaos, 2019).
- **Coastal flooding:** Exploration of a scenario where an extreme winter storm event combines with high tides, cold-season Fraser River flooding, and worst-case sea level rise (Northwest Hydraulic Consultants, 2014).
- **Pluvial flooding: E**xploration of a scenario where an extreme early summer storm occurs while the receiving environment has elevated water levels due to lingering freshet conditions.

Understanding changes to the frequency and/or magnitude of compound-event flooding due to climate change requires consideration of climate change trends across different aspects of the climate system, and their likelihood of interaction at any point in time. Moreover, compounding can occur through the interaction of physical climate change trends, with parallel socioeconomic and demographic shifts (Shrestha, 2020). For example, an assessment of climate change impacts to flooding of agricultural land within the City of Surrey (B.C Agriculture and Food Climate Action Initiative, 2014) highlighted that climate-caused increases to flooding will likely be exacerbated by land use changes, which, for example, will reduce the ability of the landscape to absorb moisture and thus increase exposure to pluvial flooding.

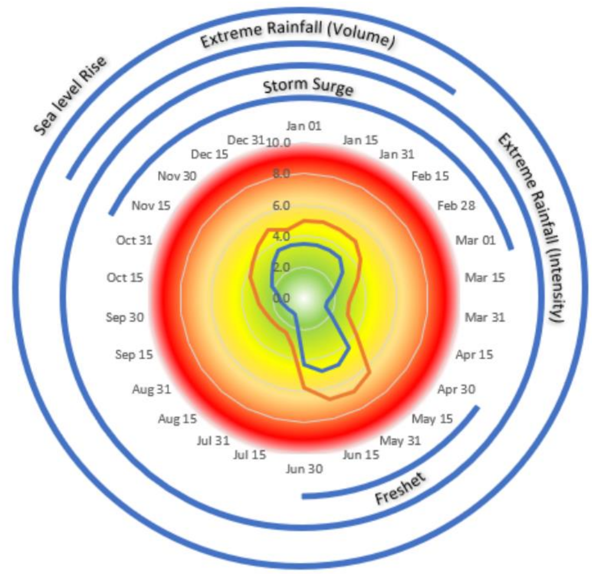


Figure 7-2
Varying Flood Likelihood Throughout the Year

Example of the changing likelihood of flood throughout the year in a coastally influenced watershed. The primary flood mechanisms are shown on outside ring; with the combined-event relative likelihood scoring shown in the colored internal ring, across a normalized scale of 0 to 10, with (red) and without (blue) the impacts of climate change (Associated Engineering, 2019).

Seasonal timing of flood mechanisms in B.C. play an important role in determining the likelihood of compound event-influenced flooding. For example, in tidally influenced areas of the Lower Mainland, two periods with potentially higher compound flood risk occur: one in the winter, as cold-season rainfall (e.g. atmospheric river landfall) coincides with storm surge; and another in spring, as freshet flooding coincides with extreme early-season convective storm rainfall. Climate change factors into this vignette as the timing, frequency, and magnitude of each individual flood mechanism can combine to create events that have not been previously experienced.

7.2 State of Science, Modelling and Data

Progress in science, modelling and data to understand the likelihood of future compound flood events requires the ability to accurately model related climate events, which in composite provide a compound flood response. Accurately capturing these related events within a model or analysis framework, and then using this framework to assess future change can be challenging. Using these frameworks to support applied decision making is still in its infancy, consistent with the immature state of more general compound event understanding and analysis (Zscheischler, et al., 2020). Different types of compound flood events, with potentially different means of analysis in the climate change context, include:

- Preconditioned compound flooding: for example, pluvial flooding that is worsened ('preconditioned') due to the presence of already-saturated soils, or hydrophobic soils from a recent wildfire. This requires careful assessment of changes to both previous/antecedent conditions, and primary flood-causing processes.
- Flooding caused by multiple simultaneous drivers: for example, combined coastal/fluvial flooding worsened by strong winds, low barometric pressure, and heavy rainfall, all resulting from a single atmospheric river landfall. This requires careful assessment of changes to multiple drivers, their potential inter-relationships, and their probability of joint occurrence.
- Temporally compounded flooding: for example, heightened fluvial flooding of a watershed due to back-to-back precipitation events. This requires multi-event or continuous simulation, instead of single annual maximum 'design storm' analyses.
- Spatially compounded flooding: for example, multiple simultaneous ice jam break-up events in upstream tributaries, leading to heightened main-stem watercourse flooding. This requires analyses that step outside of expected spatial boundaries of standard analyses.

8 CAPACITY WITHIN PROVINCE

To be successful, an integrated network of knowledgeable climate change professionals, that span research, policy, and practice related to flood hazard assessment, risk analysis and application of appropriate adaptation measures, is required across the province. These professionals must work towards a common goal including the following aspects:

- Improved understanding of acceptable approaches for assessing and applying climate change impacts for specified deliverables.
- Agreement on which climate scenarios to use.
- Technical and scientific understanding to appropriately apply available climate change data and information.
- Resource capacity building to successfully integrate additional complexity related to climate change considerations.

This investigation explores current capacity of responsible authorities within government and other professionals involved in flood hazard assessment and management. It identifies where targeted capacity-building can improve effective integration of climate change considerations into provincial flood hazard management activities including:

- Ability to collaborate with climate scientists to understand evolving scientific knowledge and best climate data use practices.
- Ability to robustly interpret flood hazard information based on future climate projections, in light of key uncertainties, including:
  - Future carbon emission pathways and scenarios
  - Differences in future climate change and flood projections between different predictive models
  - The overlap of natural and anthropogenically-driven drivers of flood conditions

To maintain consistency with the earlier sections of this report, this investigation is organized by the predominant flood types and mechanisms.

8.1 Riverine Floods: Spring Freshet

Technical and resource capacity to incorporate climate change considerations into freshet flood assessments is growing province wide. Expanding expertise is evident through the research and innovative work being led by PCIC and applied by crown-corporations such as BC Hydro. These key Provincial-organizations possess in-house province-leading hydrologic modelling experts. However, the mandate of these organizations is not focussed on flood hazard assessments and management and they are not positioned to readily support specific smaller-scale investigations. Although Provincial knowledge and capacity is growing within various ministries including ENV, MoTI and FLNRORD, the current limited technical and resource capacity impedes their ability to proactively update and incorporate climate change considerations into tools and programs. This leads to an ad hoc approach with various branches of government applying climate change considerations in different ways and to varying degrees.

A key area of concern relates to local and First Nation governments. Many communities across B.C. have been affected by spring freshet flood events in recent years, thus prompting flood risk investigations and mitigation studies to protect communities. As part of these studies, local governments are more frequently requesting that climate change impacts on such events be considered by their service providers to ensure that infrastructure upgrades and related community planning exercises are "future-proofed". To support this need, expertise in the private sector is growing with a number of engineering and environmental firms exhibiting a clear grasp on the rapidly evolving issues. However, the approaches used, and particularly the level of rigour applied to reduce uncertainties vary widely.

GAP

Consistent level of knowledge related to the impacts of climate change on flood hazard is lacking at local, regional and First Nation government level.

RECOMMENDATION

Provide ongoing educational and training opportunities for local, regional and First Nation governments to provide a consistent understanding of the impacts of climate change on flood hazard.

While some resources and technical expertise are available to local, regional and First Nation governments across the province, this capacity is highly variable and sporadic. In general, the private sector is supporting these flood hazard and risk assessments across the province. However, local, regional and First Nations governments must identify the need, define the scope, secure the funding, and manage the implementation of these studies. Establishing a minimum threshold of understanding the impacts of climate change on flood hazards would allow more consistent engagement of qualified experts to apply their knowledge to these types of assessments. As well, although many private sector organizations are improving their ability to undertake flood hazard and risk assessments related to spring freshet flood events, the current guidance allows a significant amount of interpretation and application of professional judgement which highlights a lack of standardization. A consistent framework that guides this process yet allows some flexibility to apply professional judgement would help ensure an appropriate level of analysis is undertaken.

8.2 Riverine Floods: Atmospheric Rivers

Growing awareness and concern of AR impacts to communities and infrastructure across the province has resulted in growing scientific capacity related to provincial AR processes, mechanisms and trends. However, in relation to the large and potentially growing impact that ARs have on provincial flooding, scientific capacity is still relatively limited, ad hoc, and supported by individual researcher priorities. This capacity is currently largely reflected in academic and research personnel within the province, which should be increasingly leveraged to develop customized B.C. specific AR understanding, and to develop B.C. specific short-term AR forecasts (e.g. for specific events) and long-term projections (e.g., incorporating climate change trends into AR landfall statistics). Less mature than understanding of ARs themselves, is understanding the linkages between ARs and flood events in B.C.

GAP

Information and guidance contained with "The Future of Atmospheric Rivers and Actions to Reduce Impacts to British Columbians" (Pinna Sustainability, 2014) **has been superseded by more recent research findings.**

RECOMMENDATION

Update "The Future of Atmospheric Rivers and Actions to Reduce Impacts to British Columbians" (Pinna Sustainability, 2014) with more recent provincial atmospheric river research findings and related guidance.

To improve local understanding and manage the impacts of atmospheric river events, the BC Ministry of Environment and Natural Resources Canada commissioned "The Future of Atmospheric Rivers and Actions to Reduce Impacts to British Columbians" (Pinna Sustainability, 2014) to summarize the current state of knowledge pertaining to

Atmospheric Rivers affecting B.C. More recent studies on this topic are beginning to provide initial results and, perhaps more importantly, methodological frameworks for linking changes to 'rivers in the sky' to changes in 'rivers on the ground' (Curry, Islam, Zwiers, & Dery, 2019). Greater provincial technical knowledge and capacity should be developed, particularly since atmospheric rivers are already a substantial source of flooding in coastal areas. Suitable knowledge to effectively integrate the impacts of ARs to flood hazard in B.C. requires expertise that is literate with respect to the changing impacts of ARs under climate change. This literacy will enable planning efforts to recognize when and why ARs may emerge as a new, major driver of flood hazards.

A strong model for developing atmospheric river expertise and resource capacity exists in California, where atmospheric rivers have caused widespread flood damage in the past. Responding to these impacts, the 2019-2020 State Legislature budget included a $9.25M fund to research, better understand and forecast atmospheric rivers and their change due to a changing climate. This initiative included funding for California research agencies and the California Department of Water Resources (California Legislature, 2019). A similar initiative in B.C., supporting both provincial meteorology and hydrology specialists and regional researchers, would greatly consolidate current technical and resource capacity (Dery, Sharma, & Islam, 2020).

GAP

Current capacity to assess climate change impacts related to atmospheric rivers is not widely supported at the Provincial level.

RECOMMENDATION

Support Provincial capacity to assess climate change impacts to atmospheric rivers possibly mirroring the approach taken by the State of California.

8.3 Riverine Floods: Ice Jams

At present, national expertise on riverine flooding due to ice jamming is primarily located in Alberta (Turcotte, 2020). This technical capacity is clearly reflected in numerous assessments of ice jam impacts and risk to Alberta rivers, provincial guidance, and a strong practitioner network. This weighting is likely related to the historical prevalence of materially damaging ice jam flooding in Alberta, and in particular, on the Athabasca River which was epitomized by 2020 flooding in Fort McMurray.

In contrast, less coordinated technical capacity appears to exist in B.C. Ad hoc expertise capacity is likely being developed in the course of ice jam flood assessments for particular communities, some of which include exploratory estimates of climate change impacts. These are typically based on indirect, empirically-based proxies for ice jam behaviour, rather than direct impact modelling of ice jam changes themselves (Matrix Solutions, Inc., 2018) (Northwest Hydraulic Consultants, 2009). Increased organizational capacity to develop climate change impacts to ice jam flooding in B.C. could be developed based on a jurisdictional scan of the Alberta ice jam sector network, particularly aspects of this expertise focussed on climate change impacts to ice jam fequency and severity. A similar organizational scan the Canadian Geophysical Union Committee on River Ice Processes and the Environment[1] would provide additional insight related to needs, opportunities and capacity.

GAP

There is little coordination of, and support for, ice jam flooding capacity in B.C.

RECOMMENDATION

Increase support for Provincial capacity to assess climate change impacts to ice jam flooding, that potentially mirrors the approach taken by the Province of Alberta.

[1] http://www.cripe.ca/ provides information on the "Committee on River Ice Processes and the Environment," (CRIPE).

Expert knowledge in river ice processes is derived from both educational opportunities and professional experience. Since B.C. has very limited ice engineering educational opportunities, there is a corresponding deficiency of professional experience stemming from this limitation. At times, experts from jurisdictions where more comprehensive educational opportunities exist, have supplemented local practitioners. A formalized approach to building technical and resource capacity in river ice processes in B.C., including educational opportunties, would advance this expertise and knowledge locally. Importantly, this knowledge would highlight this significant flood hazard mechanism and increase focus on addressing the corresponding flood risk.

8.4 Coastal Floods: Sea Level Rise and Storm Surge

Scientific capacity to assess climate change impacts to coastal flooding exists in the form of federal expertise hosted in-province, Provincial and municipal expertise, and significant private sector experience. Federal personnel developing national relative sea level rise datasets and coastal flood risk methods are B.C.-based (e.g. Geological Survey of Canada).

Some technical expertise around assessments of coastal flood hazard exists within the Provincial government. For example, a strategic assessment of coastal flood risk was included in the "Preliminary Strategic Climate Risk Assessment for British Columbia" (Ministry of Environment and Climate Change Strategy, 2019) which estimated the impacts of a storm surge event with a 0.2% annual exceedance probability, combined with 0.5 meters of relative sea level rise. This assessment highlights that significant technical capacity currently exists within Provincial government departments to assess coastal flooding risk, given appropriate input information regarding coastal flood likelihood and magnitude (Neale, 2020). Additional technical capacity exists at the local and regional government levels. For example, the City of Vancouver and the Capital Regional District have each commissioned recent, dedicated studies on the impacts of climate change to coastal flooding risks (Northwest Hydraulic Consultants, 2014), (AECOM, 2015) that motivated more refined follow-on assessments (Compass Resource Management, Ltd., 2016) (Associated Engineering, 2020). A variety of coastal flood assessments for other municipalities and districts include some measure of climate change considerations (Lyle & Hund, 2020), including the following:

- District of Squamish
- District of Nanaimo
- Squamish-Lillooet Regional District
- Cowichan Valley Regional District
- District of Tofino
- District of Ucluelet
- Village of Zeballos

The Coastal Flood Risk Assessment for the Capital Regional District (Associated Engineering, 2020) included increments of Relative Sea Level Rise, thereby allowing planning and policy development based on risk-based adaptive management. This incremental RSLR was applied to allow planners and decision makers to recalibrate based on future realizations of RSLR. Notably, the current state of climate knowledge did not support changes to the frequency and severity of coastal storms that would warrant modified wind and barometric pressure inputs to the impact models.

Substantial Provincial, municipal and private-sector expertise in application of climate change information to coastal flood assessments suggests that technical capacity exists within the province. In particular, private sector expertise that can support government in this specialty sector is demonstrated by healthy competition related to publicly tendered coastal flood hazard assessments in recent years. This expertise extends into the ability to integrate updated relative sea level, storm surge, and wave projections into coastal flood planning. Updating of current policy, regulations, and/or guidelines with current sea level and wave/surge projections is perhaps the largest barrier to improvement to the quality and accuracy of coastal flood planning initiatives. New regional gridded Geodetic Survey of Canada (GSC) datasets that improve estimates of RSLR are currently being developed (Tom James et al, 2020).

> GAP
>
> **Current policy, regulations and guidelines related to sea level projections embodied in Provincial guidance are significantly dated.**
>
> RECOMMENDATION
>
> **Update Provincial policy, regulations and guidelines related to sea level rise to incorporate emerging B.C.-specific relative sea level rise, and wave/storm surge projections described in this report.**

While it is clear that sea level is rising, the rate of increase into future planning horizon time scales is uncertain. Similarly, the climate change signal indicating future changes to wind and pressure off Canada's west coast are not clear enough to indicate trends related to surge and wave effects, although these possible effects are the subject of current focussed research. Due to these uncertainties, and the expectation that this information will become more certain in the future, some jurisdictions, such as the Capital Regional District (CRD) (Associated Engineering, 2020) are estimating the time horizon to achieve fixed levels of Relative Sea Level Rise, such as the expected year that 0.5, 1.0. 1.5 and 2.0 m RSLR will occur. This relative time frame allows member municipalities, electoral areas and First Nations within the CRD to complete planning activities based on a future RSLR condition, knowing approximately when that condition is expected to occur.

8.5 Pluvial Floods: Intense Rainfall

Technical and resource capacity to integrate climate change considerations into pluvial flooding assessments is largely tied to scientific knowledge around extreme rainfall events. It is notable that several nationally leading climatologists with expertise in extreme rainfall are based in British Columbia, including personnel at the Pacific Climate Impacts Consortium (PCIC) and at Environment and Climate Change Canada (ECCC). While their scope of work is not strictly focussed on extreme rainfall understanding in B.C., they do provide important support on this topic.

Since pluvial flooding can be, in many cases, directly assessed using hydrologic and hydraulic impact models, it is notable that a significant number of private consulting engineering and environmental firms are active in these types of investigations throughout the province. This practitioner-based capacity is in principle poised to develop pluvial flood assessments that are based on precipitation data derived from climate modelling and downscaling, instead of using historical design precipitation values (i.e. IDF curves). However, technical capacity is still lacking in judging the robustness of this incoming precipitation data and information. For example, assessing the extent to which sub-daily rainfall intensity, duration, and frequency information derived from statistical downscaling (e.g. IDF-CC)

> GAP
>
> **Methods for assessing climate change impacts to future short-duration extreme rainfall are not well understood by flood practitioners.**
>
> RECOMMENDATION
>
> **Establish Provincial guidance and technical training for methods of developing short-duration extreme precipitation projections that would be suitable to use in industry supported impact models.**

(Simonovic, Schardong, Gaur, & Sandink, 2020) are robust. Improving technical understanding of how future-based meteorological inputs are derived and their applicability to hydraulic modelling of pluvial floods (Associated Engineering, 2019) would be an important advancement in this respect. In practice, it is relatively straight-forward to interject future rainfall projections into pluvial flood hazard assessments. The challenge is to develop defensible future climate IDF curves that are appropriately spatially and temporally downscaled.

Notably, Environment and Climate Change Canada is developing rainfall datasets based on temperature scaling approaches that are expected to improve local rainfall statistics. As well, some local and regional governments, such as Metro Vancouver, have developed local future condition IDF curves.

8.6 Compound Event Flooding

The influence of compound events and their changing likelihood has been recognized as a key aspect for climate-resilient planning in B.C. This is highlighted across several recent Provincial reports such as “Potential Economic & Agricultural Production Impacts of Climate Change Related Flooding in the Fraser Delta” (B.C Agriculture and Food Climate Action Initiative, 2014) and the “Preliminary Strategic Climate Risk Assessment for British Columbia” (Ministry of Environment and Climate Change Strategy, 2019) that include specific case studies that explore impacts of compound event-influenced flooding. The presence of compound event discussions in these climate change-specific reports suggests that technical capacity and expertise exists, at least at the conceptual level, to develop better frameworks for assessing climate change impacts to compound flooding in B.C. However, likely mirroring the case in other jurisdictions, there is little in the way of an organized, funded compound flood event assessment in B.C. or a well-defined framework for completing these investigations.

On the practitioner side, awareness and response to compound flooding remains largely driven by experiences of past compound events as reflected in flood records, Indigenous Traditional Knowledge, and historical hydrometric data. Thus, to the extent that compounding events contributed to large historical floods, they are currently accounted for in existing guidelines, regulations, and flood mapping. However, given the very rare likelihood of extreme compound events, it is possible that the historical record contains no information on extreme compound flood events. Furthermore, this record does not contain adequate assessment of climate change driven alterations to compound event flooding. Thus, significant needs exist to improve understanding of the current state, and future climate change-driven shifts, to compound flooding risks in B.C.

Identifying critical combinations of events and their combined probabilities, especially under future climate conditions, is of particular concern. Highlighting this concern is that climate science is often focussed on a singular issue whereas a flood hazard practitioner must determine the combination of future climatic drivers and hydrologic responses that result in the worst-case scenario. Running continuous simulations of multi-year climate and impact models allow probabilistic assessments of a spectrum of hydrologic and hydraulic conditions and can effectively represent the complexities of these interactions. However, probabilistic assessments are often constrained by achievable level of effort and data availability. On the other hand, using more traditional event-based modelling introduces a variety of concerns related to level of confidence and the potential for not capturing the critical conditions.

Building technical and resource capacity to better understand compound event flooding is challenging. It requires general industry knowledge building and continued development of the underlying data needs along with commensurate resources and funding. Regardless of whether standards-based or risk-based approaches to flood hazard management are pursued by the Province, realistic estimates of the combined probabilities of events along with assurance that the critical event(s) are captured is necessary. Building this capacity and knowledge is likely best achieved through educational opportunities, sharing experiences through Professional organizations, and targeted peer review of project work.

8.7 Future Pathways

Selecting future emission pathways, time horizons and underlying GCMs are key decisions faced by government. Complicating these decisions is that the selected pathways for various activities will likely vary depending on the nature of the project and associated risk tolerance. Other agencies within Canada are also grappling with this issue; there is no aver-arching and consistent application in the selection of future emission pathways used for analysis and design. For example, the Federal Floodplain Mapping Guideline Series – Case Studies on Climate Change in Floodplain Mapping Vol.1, (Natural Resources Canada, Public Safety Canada, 2018) includes three case studies, each of which use different emission scenarios, GCMs and time-horizons.

Due to the uncertainties associated with a variety of climate change estimations including emission scenarios, climate models, downscaling and bias-correction methods, and incorporating climate information as inputs, it is apparent that flood hazard assessments must apply appropriate levels of conservatism while infrastructure projects must also allow for risk-based flexible design. These issues highlight the need for periodic and regular updates to address the impacts of non-stationary changes that will affect the expected level of service. Since significant effort is put forward to support each update to the Coupled Model Intercomparison Project (CMIP), aligning updates of guidance documents to immediately follow CMIP updates may provide a meaningful, effective and high value approach. Updates to the CMIP have occurred on an approximate 5-year cycle.

An important consideration in the selection of future emission pathways is the need to align with the scientific community and a higher likelihood of available data. For example, the data required to support application of RCP 6.0 may be lacking when compared to RCP 4.5 and RCP 8.5.

The time horizon for estimating the impacts of climate change is another important consideration. The current data supports mid 21st century hydrologic predictions, but end of 21st century predictions become significantly more uncertain. The current minimum standard related to flood hazard assessment and mitigation in the province has an AEP of 0.5% (200-year RP). This standard does not align well with future climate change projections that become increasingly uncertain beyond the turn of the century. Nevertheless, combining a relatively pessimistic future emissions pathway with risk-based flood assessments and flexible design would allow adjustments to be made as evidence becomes more supportive of the assumptions made. What constitutes “relatively pessimistic” should be revisited every five years in line with CMIP updates and with consideration of data to support longer range projections of the impacts of climate change.

A formal collaboration network of subject matter experts (SME's) would provide an opportunity to explore this complex issue and provide recommendations on selecting climate models, future emissions pathways, time horizons and related issues relative to different flood management activities including floodplain mapping, flood risk assessments and infrastructure design. Provincial members should be sourced from:

- Provincial Ministries (i.e. FLNRORD, ENV, MoTI) and Branches (i.e. River Forecast Centre)
- Provincial Crown Corporations (e.g. BC Hydro)
- NGO's and Research Institutions (e.g. Pacific Climate Impacts Consortium, Fraser Basin Council)
- Academic Institutions (i.e. UBC, SFU, UVic, UNBC)

GAP

There is a need for improved clarity related to future climate scenarios for flood hazard assessment and mitigation works,

RECOMMENDATION

Develop a formal collaboration network of subject matter experts (SME's) that would support development of guidance documentation related to application of emission pathways, climate model selection, time horizons and related issues.

This collaboration network should also engage public/private sector flood assessment practitioners such as:

- Professional organizations (e.g. Engineers & Geoscientists B.C.; Canadian Water Resources Association; Canadian Dam Association, Engineers Canada);
- Governmental organizations (e.g. Union of BC Municipalities)
- Business organizations (e.g. regional Chambers of Commerce, Insurance Industry)

8.8 Building Capacity and Collaboration

B.C. is recognized as a national leader in the context of climate change research and understanding. This includes substantial work on the topic of addressing climate change impacts to flood hazard and risk. However, barriers remain with respect to climate change integration into provincial flood hazard management. These barriers generally center around building collaboration and developing expertise and leadership.

Technical capacity to undertake world-class downscaling and flood impact modelling exists and is active in B.C., for example at the Pacific Climate Impacts Consortium and BC Hydro. However, this effort is typically under-resourced relative to the work requested of it and their mandates are not specifically directed at supporting flood hazard and risk assessments. Augmenting existing resource capacity in these and other organizations with additional human resources, tasked specifically with improving integration of climate change considerations into B.C. flood assessments, risk analsysis, and appropriate adaptation measures would directly increase the quality of B.C. flood hazard investigations.

GAP

Provincial flood impact modelling capacity is under-resourced.

RECOMMENDATION

Strengthen existing provincial downscaling and climate change/flood impact modelling capacity.

A provincial collaboration network bridging public and private climate change and flood hazard SMEs and supported by academia and research institutions could leverage and support existing networks that are impacted by climate change-induced flood hazards.

Furthermore, supporting a formal provincial collaboration network of climate change/flood hazard subject matter experts (SMEs), mandated to advance climate change considerations within flood planning in B.C. would provide an opportunity for inter-agency leveraging, knowledge sharing, and economies of scale.

GAP

There is an opportunity to leverage and support existing networks that are impacted by climate change-induced flood hazards.

RECOMMENDATION

Develop and support a provincial flood hazard assessment practitioner collaboration network that spans local, First Nation and regional governments and private sector consultants.

These networks could be leveraged to span local and regional municipal governments, and private sector consultants who carry out most provincial flood hazard assessments in practice. These networks would provide representation for Provincial, First Nation and Federal Government input. The focus would be on sharing challenges and opportunities for integrating climate change into local-scale flood hazard and risk assessments and adaptation planning.

Widespread support for increased resourcing of climate change/flood hazard initiatives would likely be greater if increased public literacy regarding potential climate-induced flood hazard and risk was developed. Up to date evidence-based, scientifically accurate, and 'well-translated' public climate change/flood literacy training would support this goal. Documentation and training from other jurisdictions (UK Meteorological Office, 2020) could be used as a template, and could take the form of:

GAP

There is a need for increased public literacy regarding potential climate-induced flood hazard and risk.

RECOMMENDATION

Develop literacy training for the public, related to climate change impacts to floods

- Expanded Provincial web-based climate information services (Province of British Columbia, 2020);
- Public engagement initiatives by Provincial and academic climate change/flood specialists; and,
- Engagement of climate change/flood specialists with Provincial, regional and municipal politicians and other influential leaders in close contact with the public.

General literacy training is needed for local government representatives, who are often tasked with activities such as developing Requests for Proposals related to flood hazard and risk assessments, reviewing submissions, and ultimately implementing the recommendations of such assessments. Literacy training would be general in nature, consistent with more technical training associated with increased provincial technical capacity discussed above, and include topics such as:

- Climate change fundamentals (e.g. observed changes, climate modelling, emission scenarios, extreme events);
- Relationship between global-scale change, and changes to local-scale measures of flooding; and,
- General best practices in developing climate-aware flood assessments.

GAP

General literacy training is needed for local government representatives.

RECOMMENDATION

Develop literacy training for local government representatives, related to climate change impacts to floods.

Technical capacity training for practitioners to integrate climate change trends into flood planning could include seminar/webinar series, workshops, or self-study initiatives, that are led by provincial flood/climate change subject matter experts and are supported by relevant professional/technical development avenues. Technical capacity development initiatives should target technical professionals, as opposed to general staff and policymakers, and be specific to physical flood mechanisms. Initiatives should include:

- Overview of methodologies for performing climate-aware flood assessments;
- Background to global climate modelling and downscaling methods;
- Development, calibration, validation and interpretation of flood-related impact modelling; and,
- Design of ensemble-based flood assessments.

GAP
There is a need for technical training for BC practitioners to integrate climate change trends into flood planning.
RECOMMENDATION
Develop and support technical capacity training for provincial practitioners to integrate climate change trends into flood planning.

Academic researchers are typically incentivized to publish in academic journals, in support of traditional researcher metrics and continued federal research funding. Incentivizing/funding B.C. flood/climate change practitioner-relevant research could increase the quantity and quality of research that could be applied to flood hazard assessments, risk analysis and appropriate adaptation measures. Support for this work could come from existing avenues including:

GAP
There is a need to support B.C. flood/climate change practitioner-relevant research.
RECOMMENDATION
Incentivize provincial academic researchers to develop practitioner-relevant academic research.

- Pacific Institute for Climate Solutions;
- Federal industry/academic programs with a specific B.C. subcomponent (e.g. the Strategic Innovation Fund and MITACS Innovate BC); and,
- Targeted partnerships between Provincial researchers and Provincial programs, as well as between researchers and regional agencies (e.g. Fraser Basin Council, Okanagan Basin Water Board, Columbia Basin Trust, Northern Development Initiative Trust)

.

9 CURRENT POLICY, REGULATIONS AND/OR GUIDELINES

This investigation explores current Provincial Policy, Regulation and Guidance related to climate change considerations in flood hazard management assessments and discusses whether this guidance should be updated.

Only a handful of key documents exist specific to Provincial Policy, Regulation and Guidance as they relate to climate change considerations in flood hazard management. The key Provincial documents include:

- Flood Hazard Area Land Use Management Guidelines (Ministry of Water, Land and Air Protection, Province of BC, Amended, 2018)
- Climate Change Adaptation Guidelines for Sea Dikes and Coastal Flood Hazard Land Use – Guidelines for Management of Coastal Flood Hazard Land Use (BC Ministry of Environment, 2011)
- Coastal Floodplain Mapping – Guidelines and Specifications (Ministry of Forests, Lands and Natural Resource Operations, 2011)

Additionally, some reports that investigate the impacts of climate change on specific areas of the province exist, such as the following reports that focus on the Lower Fraser River:

- Simulating the Effects of Sea Level Rise and Climate Change on Fraser River Flood Scenarios, (BC Ministry of Forests, Lands and Natural Resource Operations, 2014)
- Simulating the Effects of Climate Change on Fraser River Flood Scenarios – Phase 2 (Flood Safety Section Ministry of Forests Lands and Natural Resource Operations, Province of BC, 2015)

The documents listed above are supported by Professional Practice guidelines and Federal Floodplain mapping guidebooks as follows:

- Legislated Flood Assessments in a Changing Climate in BC Ver. 2.1 (EGBC, 2018)
- Case Studies on Climate Change in Floodplain Mapping, Vol. 1 (Natural Resources Canada, Public Safety Canada, 2018)
- Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation, Ver. 1.0 (Natural Resources Canada, Public Safety Canada, 2019)

In addition to the documents listed above, a large variety of supporting studies, tools and reference project summaries exist.

To maintain consistency with the earlier section of this report, this Chapter is organized by the predominant flood types and mechanisms.

9.1 Riverine Floods: Spring Freshet

In 2018, in coordination with FLNRORD and Natural Resources Canada (NRCan), EGBC released the document "Legislated Flood Assessments in a Changing Climate in B.C." (EGBC, 2018). The following guidance is provided in this document that is widely used by Engineering practitioners in the completion of flood assessments throughout the province (note: quotes are truncated for clarity, and numbered for reference in subsequent discussion):

1. larger watersheds in which flooding is dominated by spring freshet "may experience diminished flood magnitude in many years and more frequent low flows" (no reference provided).
2. "…the potential for a historically high flood will remain, since an exceptionally large winter snow accumulation followed by a sudden spring heat wave might still create extremely high runoff." (no reference provided).
3. "By time series analysis of historical precipitation and flood records, determine whether any statistically significant trend is currently detectable in … flood magnitude and/or frequency."
4. If a significant trend is not detected, "…apply a 10% upward adjustment in design discharge to account for likely future change in water input from precipitation."
5. If a significant trend is detected, "…In large (seasonally driven) basins, adjust expected flood magnitude and frequency according to the best available regionally downscaled projections of annual precipitation and snowpack magnitude, assuming that the precipitation increment will all be added to peak runoff. For snowpack, compare projections with historical records of runoff from snowpack of similar magnitude."

The authors of this report contend that this specific guidance is incomplete and potentially misleading with respect to freshet flooding. This assessment is significant, especially since freshet flooding is a dominant form of flooding throughout much of the province. Reasons for this conclusion are as follows:

- Given the diverse geography of B.C.'s large watersheds, the general guidance statement in *item 1*, above, is overly simplistic. As one example, recent hydrological modelling of the Fraser Basin, B.C.'s largest major watershed (Curry, Islam, Zwiers, & Dery, 2019) suggests the potential for significantly increased future flood magnitudes, stemming from a flood mechanism (i.e. atmospheric rivers) which is entirely unrepresented in historical flood records. This is contrary to the guidance suggested in *item 1*, and also guidance in *items 2*, *4* and *5*.
- Basing the methodology for future flood assessment on whether a historical trend in precipitation and flood records exists (*item 3 above*) runs counter to evidence-based understanding that methodologies for assessing future conditions and estimating future flows should not be based on past conditions. For example, preliminary hydrologic modelling in snow-dominated watersheds of Quebec (Huard, 2020) highlights the potential for climate change-driven 21st century flood magnitudes to first increase and then decrease. This is due to increasing winter snowfall in the presence of continued cold temperatures in the nearer term and persistently warming shoulder season temperatures that reduces overall snowpack in the longer term. This 'bi-directional' trend in flood magnitudes, which would map equivalently to flood likelihood, is not captured by any assessment based on past trends. A similar result is also suggested by unpublished watershed-specific assessments for B.C. watersheds (Jost, 2020). This highlights the potential for emergence of new processes that influence the the likelihood and magnitude of floods but are not represented in historical flood records (Curry, Islam, Zwiers, & Dery, 2019). Figure 9-1 shows the Distribution of national trends in 1-day maximum streamflow.

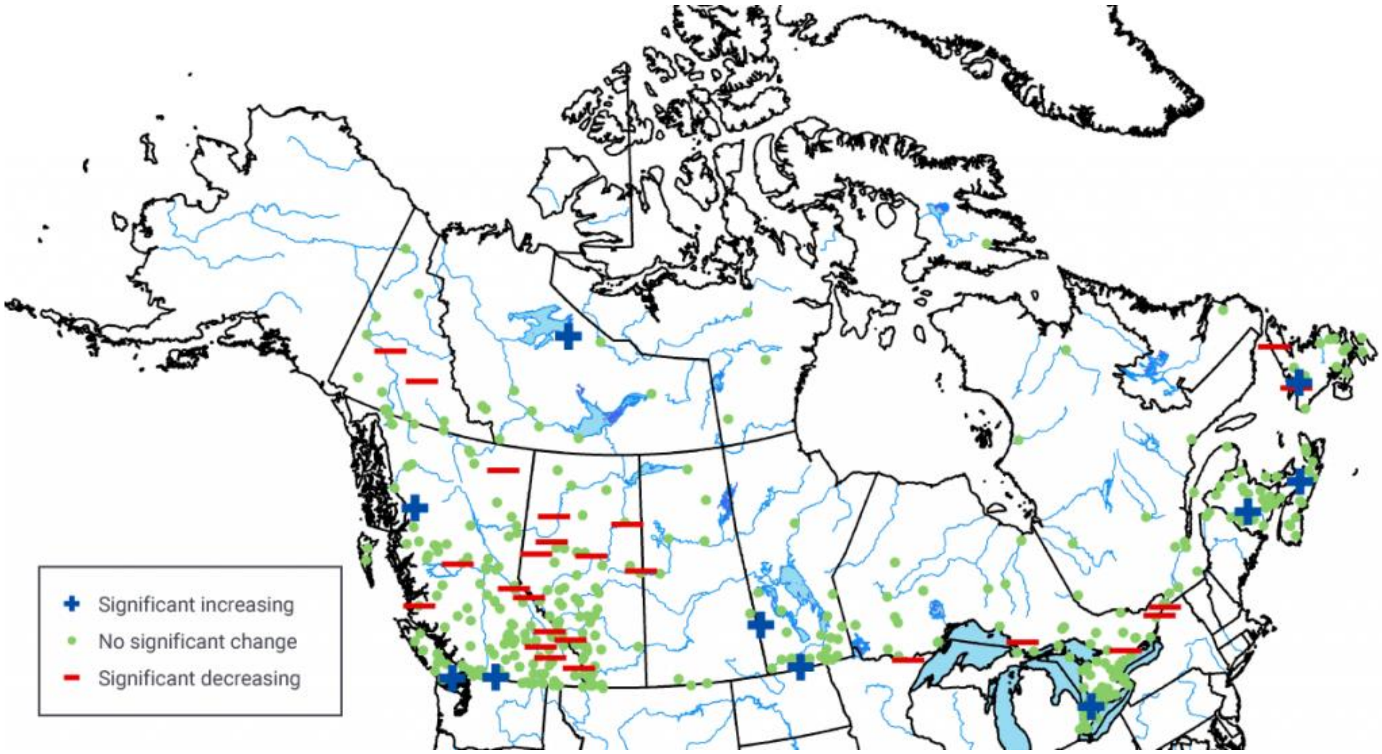


Figure 9-1
Distribution Of National Trends in 1-Day Maximum Streamflow
Shows Watercourses Included in the Reference Hydrometric Basin Network (RHBN)

Of particular note is the vast majority of RHBN watercourses in B.C. with no significantly detectable change. Flood types for nival watersheds (Figure 2-2) include trends from both open-water snowmelt flooding, and ice jam-related flooding. Lack of trend in many watersheds reflects a broader national trend, in which only 15% of RHBN watercourses exhibited a significant upward or downward trend.

- Historical trends in extreme precipitation or flooding at particular point locations are unlikely to carry statistical significance. This is largely due to natural variability inherent in these time series of extreme events, combined with record lengths that are typically insufficient to properly separate temporary trends due to internal variability (Deser, Knutti, Solomon, & Phillips, 2012). This is a primary reason that the current national-scale assessment of trends in extreme precipitation (Environment and Climate Change Canada, 2019) includes the following evidence-based statements around lack of detectable, significant trends[2]:
  - "There does not appear to be detectable trends in short-duration extreme precipitation in Canada for the country as a whole based on available station data."
  - "..the number of sites that had significant trends is not more than what one would expect from chance…"

[2] Lack of detectable historical trends in extreme precipitation counters detectable trends in seasonal or annual *average* precipitation (Figure 1-2), which are easier to detect because the act of averaging reduces the noise and thus makes a trend signal easier to detect. However, seasonal/annual average precipitation is of less relevance to flooding than extreme precipitation.

This is also mirrored in similar statements around extreme streamflow, for which equivalent issues arise (Environment and Climate Change Canada, 2019), leading to the following statements:

- "There have been no spatially consistent trends in … flood-causing factors or flooding events across the country as a whole."

The evidence presented above indicates that historical trends in precipitation and/or streamflow are not reliable as deciding factors for determining methods to assess climate change impacts to freshet flooding which is contrary to (EGBC, 2018) guidance (*items 3 and 4, above*). This statement holds true even if a significant trend is detected.

- Many watercourses in B.C. are regulated (i.e flows are modified via reservoirs and/or diversions), with direct consequences for historical records of maximum annual flood values. Assessments of trends to such records runs a significant risk of conflating management-derived trends, with trends arising from natural climate variability and change. This concern can be overcome by ensuring that data is corrected to represent natural flow conditions.
- Ambiguity around the method for determining precipitation and snowfall records that are relevant to specific flood assessment (*item 5, above*) will likely lead to errors in application of future climate information. For example:
    - Lacking more detailed instruction, point-specific precipitation information used by practitioners to satisfy (EGBC, 2018) guidance is often extracted from tools that provide estimates of future Intensity-Duration-Frequency curves at the location in question, such as IDF-CC (Simonovic, Schardong, Gaur, & Sandink, 2020), in a manner that neglects the broader watershed contribution to local-scale flooding.
    - Direction to use annual precipitation or snowpack information may result in snowpack information being incorrectly used to assess climate change impacts to pluvial flood changes, or conversely, annual precipitation being used incorrectly to assess freshet flood changes.

"An Inventory of Methods for Estimating Climate Change-Informed Design Water Levels for Floodplain Mapping" (Khaliq, Report No.: NRC-OCRE-2019-Tr-011, 2019) provides a current national-scale view of climate change impacts to national flooding, including freshet flooding. Given relatively recent publication, this guidance document has yet to be broadly distributed or integrated into Provincial equivalents (Khaliq, 2020). This guidance document provides a much more thorough, robust, and justifiable method for designing fluvial (freshet) flood analyses that include climate change considerations. Specifically in the B.C. context, fluvial flood-specific methodologies provided in this document (Khaliq, 2019) should be integrated into either an updated version of the current EGBC Guidelines (EGBC, 2018), or a superseding document.

GAP

"Legislated Flood Assessments in a Changing Climate in B.C." (EGBC, 2018) **provides inadequate guidance for climate change impacts to freshet flooding.**

RECOMMENDATION

Update "Legislated Flood Assessments in a Changing Climate in B.C." (EGBC, 2018) **to reflect current climate science and hydrologic understanding of freshet flooding. Base updated recommended methodology on "An Inventory of Methods for Estimating Climate Change-Informed Design Water Levels for Floodplain Mapping"** (Khaliq, 2019).

9.2 Riverine Floods: Atmospheric Rivers

Despite growing scientific interest and technical expertise in AR contributions to ongoing and future riverine flooding in B.C., there is little specific guidance that accurately addresses the changing impacts of ARs on flood potential. Perhaps the closest approximation to actual guidance is from "The Future of Atmospheric Rivers and Actions to Reduce Impacts to British Columbians" (Pinna Sustainability, 2014), which provides a general assessment of changes to AR events due to climate change at the provincial scale. This assessment is limited to direct precipitation impacts and thus has direct application only to pluvial flooding; atmospheric river impacts to river flow is not directly addressed. The second stage of this report, titled 'Multi-agency Risk Exploration', summarizes a series of stakeholder outreach activities centred around the concept of AR-derived risk. The outreach focussed on mortality, community isolation, and loss of critical infrastructure as key detrimental risks related to atmospheric river landfall. It also identified several regions with the highest vulnerability to atmospheric river hazards including:

- Southern Haida Gwaii (formerly Queen Charlotte Islands)
- The Kitimat coast
- The Central coast
- Mount Waddington
- The Capital region

While this source provides a useful overview of general risk and resilience principles, current rapidly evolving information on climate change impacts to both direct precipitation from ARs, and hydrologic responses to shifting AR characteristics, provides important new context that largely supersedes the scientific results in this report. These changes highlight the potential for more quantitative AR-specific guidance and the need for comprehensive AR-specific guidance, policy and regulations.

In addition to "The Future of Atmospheric Rivers and Actions to Reduce Impacts to British Columbians" (Pinna Sustainability, 2014) reporting, historic AR impacts, given their frequency, are likely implicitly represented in historical meteorological observations. This would include temperature, precipitation and streamflow and direct hydrologic measurements including discharge and stage. Thus, to the extent that these historical observations guide development of climate change factors for flood assessments contained in current professional guidance "Legislated Flood Assessments in a Changing Climate in BC" (EGBC, 2018), these factors include some measure of AR presence and change. However, methodological deficiencies in this guidance limit the usefulness of this guidance in integrating AR change. For example, impacts of climate change on ARs and on watershed specific flooding will in most cases be poorly represented by basic historic precipitation trends. Furthermore, these trends will be wholly unable to capture potentially foundational shifts in dominant watershed-specific flood regimes (e.g. from spring freshet to cold-season rainfall-driven).

GAP

"Legislated Flood Assessments in a Changing Climate in BC" (EGBC, 2018) **provides inadequate guidance for climate change impacts to atmospheric river flooding.**

RECOMMENDATION

Update "Legislated Flood Assessments in a Changing Climate in BC" (EGBC, 2018) **or superseding guidance to reflect current climate science and hydrologic understanding of atmospheric river flooding. Consult** (Khaliq, 2019) **on potential methodologies.**

9.3 Riverine Floods: Ice Jams

While ice jam flooding does play a role in determining local flood levels and has been integrated into some previous municipal flood plain assessments (e.g. Prince George, Northwest Hydraulic Consultants, 2009), little work has apparently been carried out to provide guidance on analytical approaches, policy or regulations around assessing this type of flood hazard in a changing climate (Picketts & Dyer, 2012). Guidance specific to addressing impacts of climate change related to ice jam flooding, versus general descriptions of ice jam flooding itself, is not present in the current professional guidance "Legislated Flood Assessments in a Changing Climate in BC" (EGBC, 2018).

Developing specific, quantitative ice jam flooding guidelines, including guidelines that account for climate change, is understandably difficult. As ice jam flooding, and the impacts of climate change to this flooding is site specific, it will likely be difficult to provide quantitative policy and regulations that can be applied at a provincial or even watershed scale. Instead, clear Provincial guidance supporting methodologies for assessing climate change impacts to ice jams may be most appropriate. This could be integrated into more general guidance around ice jam flood management and mitigation, which appears to be lacking at the B.C. provincial scale. Such ice jam flood methodological guidance, upon which climate change considerations could be layered, could mirror guidance available in other provinces such as "Ice Jam Flooding" (Province of Alberta, 2018), and include conceptual work flows around how to assess the impacts of climate change on ice jams (Turcotte, Burrell, & Beltaos, 2019). This could include suggestions for both top-down and bottom-up ice jam modelling and risk assessment tools.

GAP

"Legislated Flood Assessments in a Changing Climate in BC" (EGBC, 2018) **provides inadequate guidance related to the impacts of climate change on ice jam flooding.**

RECOMMENDATION

Update "Legislated Flood Assessments in a Changing Climate in BC" (EGBC, 2018) **or provide superseding guidance to reflect current climate science and hydrologic understanding of ice jam flooding. Consult "An Inventory of Methods for Estimating Climate Change-Informed Design Water Levels for Floodplain Mapping"** (Khaliq, 2019) **on possible approaches.**

9.4 Coastal Floods: Sea Level Rise and Storm Surge

Current Policy, Regulations, and/or Guidelines related to integrating climate change into coastal flooding assessments are largely based on two related 2011 reports commissioned by the Province of British Columbia:

- Climate Change Adaption Guidelines for Sea Dikes and Coastal Flood Hazard Land Use: Guidelines for Management of Coastal Flood Hazard Land Use (Ausenco Sandwell, 2011a)
- Climate Change Adaption Guidelines for Sea Dikes and Coastal Flood Hazard Land Use: Draft Policy Discussion Paper (Ausenco Sandwell, 2011b)

These reports were based in part on B.C.-specific sea level rise information from "Projected Sea Level Changes for British Columbia in the 21st Century" (Bornhold, 2008). Outcomes of the dual Ausenco Sandwell reports were formalized in Provincial guidance: "Sea Level Rise Adaptation Primer: A Toolkit to Build Adaptive Capacity on Canada's South Coasts" (The Arlington Group Planning + Architecture Inc., 2013) and Amendment Sections 3.5 and 3.6 of the "Flood Hazard Area Land Use Management Guidelines" (Province of British Columbia, 2018). Of particular importance is the guidance in these documents related to future eustatic (i.e. non-relative) sea level change, which recommends that future eustatic sea level rise for British Columbia should be assumed to occur at a rate of 1 cm/year. This leads to time horizon-specific sea level rise values of:

- 0.5 m of sea level rise by 2050
- 1.0 m of sea level rise by 2100
- 2.0 m of sea level rise by 2200

This guidance is originally based on what appears to be a visual best fit analysis in (Ausenco Sandwell, 2011a) of a line that crosses well-rounded increments of change at well-rounded duration periods, while being bracketed by an estimate of low, median and high increments of sea level change. This estimate appears to reference a projection range that is summarized in the 2009 United Nations Intergovernmental Panel on Climate Change Copenhagen Diagnosis report (United Nations Intergovernmental Panel on Climate Change, 2009). The analysis and resultant guidance have become very influential in provincial coastal flood planning (Lyle & Hund, 2020), as 'rules of thumb' to apply to the Relative Sea Level Rise (RSLR) term of the flood construction level equation presented earlier in this report. For example, extensive and consequential City of Vancouver coastal flood planning analyses utilized these sea level rise increments in scenario analysis (City of Vancouver, 2020).

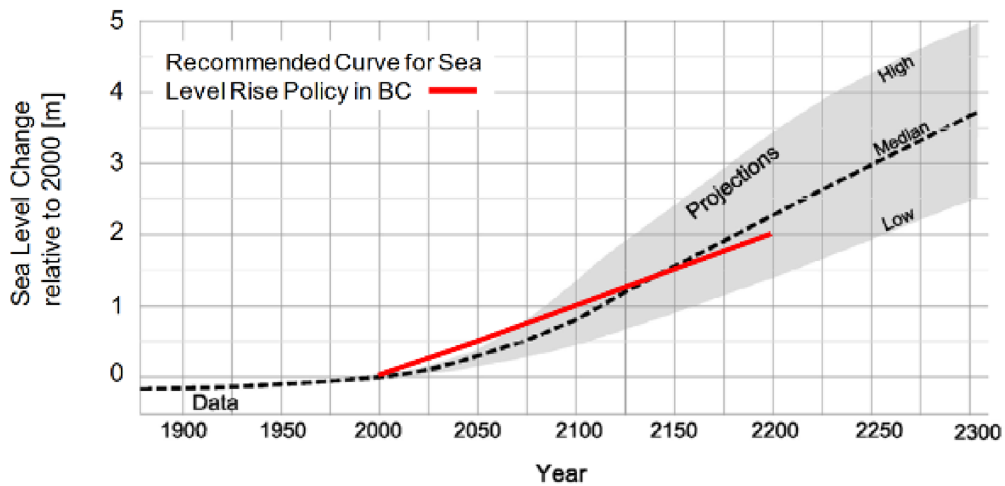


Figure 9-2
Recommended Curve for Sea Level Rise Policy in B.C.

(Ausenco Sandwell, 2011a)

These time increments represent original sea level research projections that are nearly 20 years old, given the delay between actual scientific development, publication, integration into (United Nations Intergovernmental Panel on Climate Change, 2009), uptake by (Ausenco Sandwell, 2011b) and subsequent inclusion into guidance documents. An update to these values, as recommended by (Ausenco Sandwell, 2011a), is thus overdue. Substantial additional information exists around global and regional relative sea level and wave/surge changes, as noted previously. Recommendations provided in this Section and Section 8.4 should be applied to update official guidance documents. Even if provincial sea level rise estimates do not change considerably if and when this new information is applied, an update is still recommended so that coastal flood planning decisions are professionally defensible and justified by the latest climate science.

9.5 Pluvial Floods: Intense Rainfall

Current operational guidance around treatment of climate change to pluvial flooding used by practitioners appears to be largely based on “Legislated Flood Assessments in a Changing Climate in BC” (EGBC, 2018). In this guidance, brief attention is paid to means of producing short-duration precipitation event projections, However, this discussion includes some inaccuracies related to guidance, and some information that is accurate in principle but insufficient as a basis for application to real projects. For example, general recommendations for use of regional climate models (e.g. dynamical downscaling) and multiple model simulations (e.g. ensembles) are inadequate. Ultimately, the methodology recommended for integrating climate change into pluvial flood assessments states:

- “When IDF curves are to be applied, review current IDF curves and apply results of stormwater runoff modelling appropriate for expected land surface conditions.”
- “In smaller basins, adjust IDF curves for expected future precipitation climate and apply the results of stormwater runoff modelling appropriate for expected future land surface conditions.”

The choice of method, both of which are qualitatively vague and similar, depends on the detection of a trend in historical extreme rainfall, which itself is a poor deciding factor as previously discussed.

In contrast to this source of primary Provincial guidance, “An Inventory of Methods for Estimating Climate Change-Informed Design Water Levels for Floodplain Mapping” (Khaliq, Report No.: NRC-OCRE-2019-Tr-011, 2019) provides more complete guidelines for assessing climate change impacts to pluvial events, including reviews of recent studies which used different approaches for developing estimates of future extreme rainfall in the form of modified IDF curves. In this guidance, notable attention is paid to Clausius-Clapeyron temperature-based scaling approaches, which relate future precipitation changes to relatively well-constrained temperature shifts. This arguably places estimates of future change on more solid physical ground than approaches that strictly rely on historical relationships between measures of average (i.e. daily and longer) and extreme (i.e. sub-daily) precipitation. While this guidance is still not concrete, it provides a more mature assessment of methods to assess pluvial flooding than “Legislated Flood Assessments in a Changing Climate in BC” (EGBC, 2018).

GAP

“Legislated Flood Assessments in a Changing Climate in BC” (EGBC, 2018) provides inadequate guidance for climate change impacts to coastal flooding.

RECOMMENDATION

Update “Legislated Flood Assessments in a Changing Climate in BC” (EGBC, 2018), (Ausenco Sandwell, 2011a), (Ausenco Sandwell, 2011b), and the “Flood Hazard Area Land Use Management Guidelines” (Province of British Columbia, 2018). or superseding guidance to reflect current climate science and sea level understanding of coastal flooding. Consult An inventory of methods for estimating climate change-informed design water levels for floodplain mapping (Khaliq, 2019) on possible methodologies.

GAP

“Legislated Flood Assessments in a Changing Climate in BC” (EGBC, 2018) **provides inadequate guidance for climate change impacts to pluvial flooding.**

RECOMMENDATION

Update “Legislated Flood Assessments in a Changing Climate in BC” (EGBC, 2018) **or superseding guidance to reflect current climate science and hydrologic understanding of pluvial flooding. Consult “Development, Interpretation, and Use of Rainfall Intensity-Duration-Frequency (IDF) Information: Guidelines for Canadian Water Resources Practitioners”** (CSA Group, 2019) **and “An Inventory of Methods for Estimating Climate Change-Informed Design Water Levels for Floodplain Mapping”** (Khaliq, 2019)-**on possible methodologies.**

Despite the current guidance, advancements are being made in the development of IDF curve data. Metro Vancouver recently developed IDF curves for the region and some local municipalities have developed short-duration rainfall statistics. More recently, Canadian Standards Association published a Technical Guide titled "Development interpretation, and use of rainfall intensity-duration-frequency (IDF) information: Guideline for Canadian water resources practitioners" (CSA Group, 2019). This guideline represents a first attempt to assemble methodologies, assumptions, and limitations of incorporating new rainfall statistics into the development of IDF curves into a single document. This guidance, which recommends a temperature scaling approach, should now be used by hydrologists and professionals practicing in BC to develop and use short-duration precipitation data in pluvial flood hazard assessments.

Once developed, the climate informed IDF curves can be used in much the same way as historical curves. The authors note that economic losses from urban drainage flooding has increased and is a leading cause of flood damage in Canada. Most often urban drainage design criterion is established by local government and has not attracted much attention from senior levels of government. However, recognizing the increasing flood hazard experienced by increasingly urbanizing areas combined with changes to short-duration rainfall, this issue should no longer be ignored. The Province should develop guidance that sets the minimum standard for urban drainage in a changing climate including development of rainfall statistics, assessment of minor drainage systems, major overland flow paths, and compound events that can exacerbate urban flooding.

GAP

Minimum standards for urban drainage have not been established by the Province.

RECOMMENDATION

Update "Legislated Flood Assessments in a Changing Climate in BC" (EGBC, 2018) or develop superseding guidance that sets the minimum standard for urban drainage in a changing climate including developing rainfall statistics and addressing the flood risk continuum posed by compound events that can exacerbate urban flooding.

9.6 Compound Event Flooding

Current guidelines are largely silent on the topic of climate change influences on compound events, and regulations around climate change impacts to compound floods are non-existent. "Legislated Flood Assessments in a Changing Climate in BC" (EGBC, 2018) does not explicitly consider compound events in its guidance related to riverine flooding. Similarly, "Climate Change Adaption Guidelines for Sea Dikes and Coastal Flood Hazard Land Use: Guidelines for Management of Coastal Flood Hazard Land Use" (Ausenco Sandwell, 2011a) and subsequent reporting "Sea Level Rise Adaptation Primer: A Toolkit to Build Adaptive Capacity on Canada's South Coasts" (The Arlington Group Planning + Architecture Inc., 2013) do not appear to provide guidance on compound events related to sea level rise-specific coastal flooding. Thus, recent studies, assessments and reports which have accounted for compound flood events, appear to have done so using in-house methodologies that do not conform to broader frameworks or standards. Therefore, while recognition of the importance of compound event flooding is growing, little in the way of tangible policy, regulations or guidelines appears to exist.

GAP

"Legislated Flood Assessments in a Changing Climate in BC" (EGBC, 2018) provides inadequate guidance for climate change impacts to compound flood events.

RECOMMENDATION

Update "Legislated Flood Assessments in a Changing Climate in BC" (EGBC, 2018) or develop superseding guidance to reflect current climate science and hydrologic understanding of compound flooding. Consult "An inventory of methods for estimating climate change-informed design water levels for floodplain mapping" (Khaliq, 2019) for potential methodologies.

9.7 Provincial Guidance

Overall, the flood hazard assessment guidance in a changing climate that is available to practitioners is derived primarily from Professional Practice guidelines, Federal sources, and a variety of related studies. There is a notable lack of guidance from Provincial sources. However, a significant portion of this void is filled by "Legislated Flood Assessments in a Changing Climate in BC" (EGBC, 2018) which is notably supported by FLNRO and NRCan. The Federal Government, through the Federal Floodplain Mapping Series, is also trying to develop National Standards for integrating climate change considerations into flood hazard and risk assessments. Nevertheless, the Professional guidance lacks a comprehensive perspective that brings together the needs of government to mitigate flood risk in a changing climate with Provincial policy, legislation and regulation. Ultimately, key decisions need to be made by the Province so that they can be formalized through legislation, regulation and guidance documents. Examples of key policy decisions include selecting emission scenarios and planning time horizons for assessments. As each Policy decision is made, the impacts of climate change should be inter-woven into the fabric of the legislation, regulation and guidance related to flood hazard management. Many of the recommendations contained in this report and directed towards updating "Legislated Flood Assessments in a Changing Climate in BC" (EGBC, 2018) could be equally applied to new legislation and guidelines that are developed by the Province. Ideally, parallel guidance would be provided by the Province that provides clarity on commentary provided in the Professional Practice Guidance.

GAP

There is a notable void in climate change guidance from Provincial sources.

RECOMMENDATION

Develop Provincial guidance that parallels and clarifies commentary provided in "Legislated Flood Assessments in a Changing Climate in BC" (EGBC, 2018).

10 RECOMMENDATIONS

As part of this report, recommendations were developed based on the identification of key gaps, limitations and deficiencies related to the impacts of climate change on flood hazard in the categories of:

1) Current state of understanding;
2) Current state of science, models and data;
3) Current capacity within the province; and,
4) Current policy, regulations and/or guidelines.

These gaps, particularly regarding categories 3) and 4), closely reflect those identified in recent efforts examining integration of climate change considerations into flood planning in the Cities of Surrey and Vancouver (Oulahen, Klein, Mortsch, O-Connell, & Harford, 2018), indicating a consistency of theme that reinforces this report's primary recommendations. These recommendations are summarized below and include and expand on specific recommendations identified throughout the report. Any costs provided are Class D estimates, with more work required to develop finer detail related to specific activities. It is hoped that the recommendations provided herein spur action towards a coordinated, province-wide, flood planning framework that includes climate change considerations in a consistent, robust and future-proofed manner.

10.1 B.1-1: Current State of Understanding

Actionable recommendations for closing gaps in flood-relevant climate change models and data fall into several general categories. Recommendations within each area shown in Figure 10-1 are predicated on sufficient technical and scientific capacity to undertake the necessary actions to understand drivers of change to predominant provincial flood mechanisms. The recommendations are primarily targeted at provincial-scale initiatives, that would benefit regional and municipal-scale (incl. First Nations) flood assessments via availability of improved, maintained, and standardized model and data products.

Figure 10-1
Primary Measures of Climate Change Related to Major Provincial Flood Mechanisms

Understanding changes to each of these flood mechanisms due to climate change involves assessing changes to the relevant measures of climate change, using appropriately sourced models, analyses, and data.

- **Undertake a jurisdictional scan for other provincial/state/national jurisdictions with advanced capacity regarding integration of climate change into flood hazard assessments ($50,000 one-time cost).** Scan provinces/states/nations with known vulnerabilities to different flood mechanisms, to find advances that could be applied in the B.C. context. Potential jurisdictional scan targets include:
  - State of California: in response to atmospheric river impacts, California has developed a strong state-specific atmospheric river impacts research program, including an explicit focus on assessing/responding to climate change-regulated shifts to atmospheric river hazards.
  - Province of Alberta: in response to ice jam and freshet flooding impacts, Alberta has developed strong provincial, academic and private sector technical and resource capacity on climate change impacts to freshet ice jam flooding.
  - Country of Netherlands: in response to sea level rise impacts, the Netherlands has developed a strong country-specific coastal flooding research program, that is closely integrated into national adaptation strategies.

10.2 B.1-2: Current State of Science, Models and Data

Application of the impacts of climate change considerations to flood hazard assessment is rapidly evolving and warrants monitoring of advancements in understanding, data availability, and modelling approaches including the following:

- **Consistently monitor ongoing GCM developments for new and improved flood-relevant information ($25,000/year)**. For example, in the near-term (i.e. 1-3 years), transition to Coupled Model Intercomparison Project 6 GCM-based data and products for integration into downscaling and impact modelling. In longer-term (i.e. 3-10 years), continue to monitor ability of GCMs to *directly* produce simulation output for use in flood assessments.
- **Consistently monitor advances in assessing impacts of climate change and flood science knowledge related to predominant flood mechanisms and update operational datasets accordingly ($50,000/year).** For example, monitor emerging science and data regarding:
  - Potential for watershed-specific transitions from freshet towards pluvial flood regimes;
  - Climate change impacts to regional atmospheric river landfalls;
  - Global sea level rise; regional sea level, wave and surge trends; and, regional vertical land motion;
  - Understanding of climate change-regulated shifts to frequency/severity of extreme short-duration precipitation events; and,
  - Changing probabilities of compound flooding events.

Develop Province-specific methods, models, and data

To improve consistency and to adopt appropriate levels of rigour to reduce uncertainty in climate-informed flood hazard assessments, supporting methodologies and data should be developed including:

- **Develop B.C.-specific downscaling frameworks ($500,000 start-up cost; $100,000/year).** In particular:
  - Develop B.C.-specific dynamical downscaling via B.C.-specific, ensemble-based regional climate model frameworks;
  - Develop B.C.-specific statistical downscaling via existing ensemble-based statistical downscaling frameworks, and emerging multivariate techniques that preserve critical event-specific relationships between flood-relevant climate parameters; and,
  - Develop and distribute province-wide downscaled climate datasets at daily or sub-daily resolution.
- **Expand Provincial weather, climate and water observation/monitoring efforts with a recognized target of improving climate model validation and downscaling for flood-relevant applications ($500,000 start-up cost; $250,000/year).** This work would also directly support direct observation-based flood forecasting activities. In particular, expand:
  - Permanent manned/automated weather and climate stations at remote locations, northern locations, and high elevations (riverine flooding);
  - Provincial snow surveys, specifically at mid (i.e. transitional zone) elevation locations (freshet flooding);
  - Flood-specific, location-specific hydrologic monitoring during winter season (ice jam flooding); freshet season (freshet flooding); summer season (pluvial flooding);
  - Radar and satellite-based meteorological data acquisitions of maritime wind, wave and weather conditions (coastal and atmospheric river-based flooding); and,
  - Coastal locations where long-term vertical land motion measurements are recorded (coastal flooding).

- **Develop and maintain B.C.-specific modelling and analysis frameworks for flood mechanism-specific, local-scale impact models that can be applied by qualified practitioners at local scales ($1,000,000 start-up cost, $500,000/year).** Develop B.C.-specific modelling and analysis frameworks for:
  - Freshet flooding, that use freshet-specific calibration techniques, statistics, and observational targets (possibly building upon RFC's CLEVER);
  - Ice jam flooding, that uses local empirical relationships between ice jam flooding, weather/climate conditions, and/or winter-calibrated hydrologic modelling;
  - Coastal flooding, that integrates data and information from the latest available climate-regulated inputs including wind, barometric pressure and RSLR; and,
  - Extreme rainfall, that uses scientifically defensible methods for assessing changes to short-duration rainfall.

10.3 B.1-3: Current Capacity within Province

Recommendations related to capacity-building to integrate climate change into provincial flood hazard and risk assessments are derived from barriers identified in this report (Oulahen, Klein, Mortsch, O-Connell, & Harford, 2018) and center around building collaboration and developing expertise and leadership.

Build Collaboration

Support the development of a collaboration network bridging climate change science and flood hazard expertise with participation from the public and private sector and participation from academia and research institutions. ($20,000/year). Leverage and support existing networks that are impacted by climate change-induced changes to flood risk including:

- Professional organizations (e.g. Engineers & Geoscientists B.C.; Canadian Water Resources Association; Canadian Dam Association, Engineers Canada);
- Governmental organizations (e.g. First Nations, Union of BC Municipalities); and,
- Business organizations (e.g. regional Chambers of Commerce, Insurance Industry).

And link to broader experts from:

- Environment and Climate Change Canada
- Geological Survey of Canada
- National Research Council
- Natural Resources Canada
- Other Provinces of Canada and Yukon Territory;
- US States of Washington, Oregon, and California
- F.E.M.A (Federal Emergency Management Authority)

- **Develop and support a Provincial collaboration network of climate change/flood hazard subject matter experts (SMEs), mandated to advance climate change considerations within flood planning in B.C. ($20,000/year).** A formal collaboration network of subject matter experts would provide an opportunity for inter-agency leveraging, knowledge sharing, and economies of scale. Provincial members should be sourced from:
  - Provincial Ministries (i.e. FLNRORD, ENV, MoTI) and Branches (i.e. River Forecast Centre)
  - Provincial Crown Corporations (e.g. BC Hydro)
  - First Nations

  - NGO's and Research Institutions (e.g. Pacific Climate Impacts Consortium, Fraser Basin Council)
  - Academic Institutions (i.e. UBC, SFU, UVic, UNBC)

- **Develop and support a provincial flood hazard management practitioner collaboration network ($20,000/year).** Leverage existing networks spanning local, and regional governments, and private sector consultants who carry out most provincial flood hazard and risk assessments in practice. Provide representation space for Provincial, local, First Nation and Federal Government input. Focus specifically on sharing challenges and opportunities for integrating climate change into local-scale flood hazard assessments and planning, and to the extent possible, distinguish this topic from discussions related to other non-climate change specific flood assessment challenges.

Develop Expertise and Leadership

- **Recognize and celebrate existing capacity ($20,000 one-time cost).** Already, B.C. is recognized as a national leader in the context of climate change expertise. This includes substantial work addressing climate change impacts to flood hazard and risk. Before additional capacity is developed, existing expertise and leadership should be recognized and celebrated. This would improve morale among current specialists and practitioners. It would also provide important visibility and positive public relations for current accomplishments, with direct benefits to expansion of this capability in the future. This could be accomplished in a number of ways such as by profiling the accomplishments in industry publications (i.e. EGBC's Innovation magazine), through industry galas (i.e. Canadian Consulting Engineering Awards Gala) or through public forums such as provincially distributed newspapers or television interview requests.
- **Strengthen existing Provincial downscaling and climate change/flood impact modelling capacity ($100,000/year).** World-class downscaling and flood impact modelling expertise exists and is active in B.C., for example at:
  - PCIC
  - River Forecast Centre
  - BC Hydro

  However, this effort is typically under-resourced relative to the work requested of it. Augmenting existing technical capacity in these and other organizations with additional human resources, tasked specifically with improving integration of climate change considerations into B.C. flood hazard assessments, would directly increase the quality of B.C. flood hazard investigations.

- **Develop 'Climate 101' literacy training for the public, related to climate change impacts to floods ($50,000/year).** Widespread support for increased resourcing of climate change/flood hazard initiatives would likely be greater if increased public literacy regarding potential climate-induced flood hazard and risk was developed. Up to date evidence-based, scientifically accurate, and 'well-translated' public climate change/flood literacy training would support this goal. Documentation and training from other jurisdictions (UK Meteorological Office, 2020) could be used as a template, and could take the form of:
  - Expanded Provincial web-based climate information services (i.e. Environmental Reporting BC, Climate Change Indicators (Province of British Columbia, 2020))
  - Public engagement initiatives by Provincial and academic climate change/flood specialists; and,
  - Engagement of climate change/flood specialists with Provincial, regional and municipal politicians and other influential leaders in close contact with the public.
- **Develop 'Climate 201' literacy training for local, regional and First Nation government representatives, related to climate change impacts to floods ($50,000/year).** Support general literacy training for local, regional and First Nation government representatives, who are often tasked with activities such as developing Requests for Proposals related to flood hazard and risk assessments, reviewing submissions, and ultimately implementing the recommendations of such assessments. Literacy training would be general in nature, consistent with more technical training associated with increased provincial technical capacity discussed above, and include topics such as:
  - Climate change fundamentals (e.g. observed changes, climate modelling, emission scenarios, extreme events);
  - Relationship between global-scale change, and changes to local-scale measures of flooding;
  - General best practices in developing climate-aware flood assessments.
- **Develop and support 'Climate 301' technical capacity training for provincial practitioners to integrate climate change trends into flood planning ($50,000/year).** Efforts could include seminar/webinar series, workshops, or self-study initiatives, that are led by provincial flood/climate change subject matter experts and are supported by relevant professional/technical development avenues[3]. Technical capacity development initiatives should target technical professionals, as opposed to general staff and policymakers, and be specific to physical flood mechanisms. Initiatives should include:
  - Overview of methodologies for performing climate-aware flood assessments;
  - Background to global climate modelling and downscaling methods;
  - Development, calibration, validation and interpretation of flood-related impact modelling; and,
  - Design of ensemble-based flood assessments.
- **Incentivize provincial academic researchers to develop practitioner-relevant academic research ($100,000/year).** Academic researchers are typically incentivized to publish in academic journals, in support of traditional researcher metrics and continued federal research funding. Incentivizing/funding B.C. flood/climate change practitioner-relevant research could increase the quantity and quality of research that could be applied to flood hazard management in B.C. Support for this work could come from existing avenues including:
  - Pacific Institute for Climate Solutions.

[3] For example, provincial employee Leave for Learning & Professional Development options (https://www2.gov.bc.ca/gov/content/careers-myhr/all-employees/leave-time-off/learning-professional-development); or Engineers & Geoscientists BC Professional Development requirements (https://www.egbc.ca/Practice-Resources/Professional-Development)

- Federal industry/academic programs with a specific B.C. subcomponent, e.g. the Strategic Innovation Fund[4] and MITACS Innovate BC[5].
- Targeted partnerships between provincial researchers and provincial programs, as well as between researchers and regional agencies (e.g. Fraser Basin Council, Okanagan Basin Water Board, Columbia Basin Trust, Northern Development Initiative Trust)

10.4 B.1-4: Current Policy, Regulations and/or Guidelines

Recommendations related to climate change integration into Provincial flood hazard assessment policies, tools, regulation and guidance are limited by a general absence of this content in operational flood planning regulation and guidance documents. This largely reflects the historical lack of need for this guidance when future flooding was expected to occur with the same frequency and magnitude and driven by the same characteristics as historical flooding. Recommendations presented here thus relate to the few extant, and applied, climate change/flood guidance documents that exist in the provincial context, and/or to policies, guidance, tools, or guidance that arguably should be developed to better manage climate change integration into flood hazard assessments and adaptation planning.

- **Support a mechanism for regular updating of B.C. flood-relevant climate change science and data within Provincial guidance, policy and regulations ($50,000/year).** This would ensure that guidance documents, which should primarily describe foundational methodological toolchains and concepts instead of specific models or toolchain step-specific techniques (Khaliq, 2019), do not become outdated (Khaliq, 2020).
- **Develop and/or expand Provincial standards for climate and hydrology data ($25,000/year).** Formalize and codify standards for producing, managing and reporting flood and climate change data. Standards should adopt and leverage broader standardization efforts, including for example:
    - Probability exceedance terminologies
    - Climate and Forecast (CF) metadata convention
    - GIT version controlling
    - netCDF, HDF and GRIB file formats
    - OpenDAP and Globus data sharing methods
- **Develop guidance and frameworks for ensemble approaches in flood assessments ($100,000 start-up cost).** Develop evidence-based minimum requirements for use of ensembles in producing, interpreting and reporting changes to historical and future climate and flood conditions. Ensemble-specific requirements should be developed for:
    - Disaggregating signal from noise in historical extreme climate and flood conditions;
    - Identifying trends in future climate and flood conditions and disaggregating these from noise; and,
    - Improving statistical measures of changes to flood conditions.

[4] https://www2.gov.bc.ca/gov/content/employment-business/economic-development/funding-and-grants/strategic-innovation-fund
[5] https://innovatebc.ca/what-we-offer/get-funding/mitacs-innovate-bc-program/

Existing Guidance

In 2018, EGBC produced a document titled “Legislated Flood Assessments in a Changing Climate in BC” (EGBC, 2018). In this document, non-binding guidelines described how to incorporate climate change into riverine and/or pluvial flood assessments. This guidance has now become the de facto approach for “incorporating climate change” into actionable flood hazard assessments province-wide, making this document significantly influential.

However, as noted in recommendations contained in this investigation there remains significant room to improve these guidelines, so they are more applicable to assessing climate change impacts to specific hydrologic conditions that influence the likelihood and magnitude of specific flood hazards. This leads to the following general recommendation:

- **Update or replace guidance for considering climate change within fluvial flood assessments within “Legislated Flood Assessments in a Changing Climate in BC”** (EGBC, 2018) **with a more robust methodology, either in a revised version of this document or a superseding guidance document produced by EGBC or others. Provide guidance that is consistent with the conceptual approach and methods outlined in the National Research Council guidance document “An inventory of methods for estimating climate change-informed design water levels for floodplain mapping”** (Khaliq, 2019)**. Include specific guidance related to integrating climate change considerations into riverine flooding related to freshets, ice jams, atmospheric rivers, and compound events. Provide separate guidance for pluvial flooding and coastal flooding (see subsequent recommendations) ($150,000).**

- **Update or replace guidance for considering climate change within pluvial flood assessments within “Legislated Flood Assessments in a Changing Climate in BC”** (EGBC, 2018) **with a more robust methodology, either in a revised version of this document or a superseding guidance document produced by EGBC or others. Provide guidance that is consistent with the conceptual approach and methods outlined in Canadian Standards Association’s technical guide “Development interpretation, and use of rainfall intensity-duration-frequency (IDF)information: Guideline for Canadian water resources practitioners” (CSA Group, 2019) and the National Research Council guidance document “An inventory of methods for estimating climate change-informed design water levels for floodplain mapping”** (Khaliq, 2019)**. Increase consideration of urban drainage flood risk, particularly at the interfaces between fluvial, pluvial, and coastal regimes. ($100,000).**

In the coastal flooding context, Ausenco Sandwell developed a document titled “Climate Change Adaption Guidelines for Sea Dikes and Coastal Flood Hazard Land Use: Guidelines for Management of Coastal Flood Hazard Land Use” (BC Ministry of Environment, 2011). This report provided recommendations regarding sea level rise projections in the B.C. context, and included a general recommendation of planning for 0.1 metres of “global sea level allowance” per decade from 2000 (e.g. 1 m by year 2100). Combined with local assessments of vertical coastal land motion (where available) historical tide, surge, wave effects, and additional freeboard considerations, this estimate of sea level rise was translated into coastal flood measures including determination of flood construction levels.

As noted earlier in this report and in the original Ausenco Sandwell document, more recent information should be integrated into a revised and updated version of this guidance. This leads to the following recommendation:

- **Update sea level rise information in "Legislated Flood Assessments in a Changing Climate in B.C."** (EGBC, 2018)**, "Climate Change Adaption Guidelines for Sea Dikes and Coastal Flood Hazard Land Use: Guidelines for Management of Coastal Flood Hazard Land Use"** (BC Ministry of Environment, 2011) **and the "Flood Hazard Area Land Use Management Guidelines"** (Ministry of Water, Land and Air Protection, Province of BC, Amended, 2018) **with new and soon-emerging information regarding projected global and B.C.-specific sea level change, expected changes to B.C. wave action and storm surges, and coastal vertical land motion. Update discussion of coastal flooding from the updated or superseded version of** (EGBC, 2018) **($150,000).**

Key decisions need to be made by the Province so that they can be formalized through legislation and guidance documents. As each Policy decision is made, the impacts of climate change should be inter-woven into the fabric of the supporting legislation, regulation and guidance. Many of the recommendations contained in this report and directed towards updating "Legislated Flood Assessments in a Changing Climate in BC" (EGBC, 2018) could be equally applied to new legislation and guidelines that are developed by the Province. Ideally, parallel guidance would be provided by the Province that provides clarity on commentary provided in the Professional Practice Guidance.

Develop Provincial climate change guidance that parallels and clarifies commentary provided in "Legislated Flood Assessments in a Changing Climate in BC" (EGBC, 2018) **($400,000).**

10.5 Recommendation Summary

The specific recommendations and costs contained in Sections 10.1-10.4 of this report are condensed into Table 10-1. As well, Appendix E contains a summary of callout boxes contained throughout the report.

Table 10-1
Recommendations and Class D Cost Estimate

Action Type	Action Number	Recommendation	One-time Cost ($)	Annual Cost ($)
B-1.1: Current State of Understanding	1	Undertake a jurisdictional scan for other provincial/state/national jurisdictions with advanced capacity regarding integration of climate change into flood hazard assessments	$ 50,000	
B-1-2: Current State of Science, Models and Data	1	Consistently monitor ongoing GCM developments for new and improved flood-relevant information		$ 25,000
	2	Consistently monitor advances in assessing impacts of climate change and flood science knowledge related to predominant flood mechanisms and update operational datasets accordingly		$ 50,000
	3	Develop B.C.-specific downscaling frameworks.	$ 500,000	$ 100,000
	4	Expand Provincial weather, climate and water observation/monitoring efforts with a recognized target of improving climate model validation and downscaling for flood-relevant applications.	$ 500,000	$ 250,000
	5	Develop and maintain B.C.-specific modelling and analysis frameworks for flood mechanism-specific, local-scale impact models that can be applied by qualified practitioners at local scales.	$ 1,000,000	$ 500,000
B-1.3: Current Capacity within Province	1	Support the development of a collaboration network bridging climate change and flood hazard expertise with participation from the public and private sector and participation from academia and research institutions.		$ 20,000
	2	Develop and support a Provincial collaboration network of climate change/flood hazard subject matter experts (SMEs), mandated to advance climate change considerations within flood planning in B.C.		$ 20,000
	3	Develop and support a provincial flood hazard assessment practitioner collaboration network.		$ 20,000
	4	Recognize and celebrate existing capacity.	$ 20,000	
	5	Strengthen existing Provincial downscaling and climate change/flood impact modelling capacity.		$ 100,000
	6	Develop 'Climate 101' literacy training for the public, related to climate change impacts to floods.		$ 50,000
	7	Develop 'Climate 201' literacy training for local government representatives, related to climate change impacts to floods.		$ 50,000
	8	Develop and support 'Climate 301' technical capacity training for provincial practitioners to integrate climate change trends into flood planning.		$ 50,000
	9	Incentivize provincial academic researchers to develop practitioner-relevant academic research.		$ 100,000
B-1.4: Current Policy, Regulations and/or Guidelines	1	Support a mechanism for regular updating of B.C. flood-relevant climate change science and data within Provincial guidance, policy and regulations.		$ 50,000
	2	Develop and/or expand Provincial standards for climate and hydrology data.		$ 25,000
	3	Develop guidance and frameworks for ensemble approaches in flood assessments.	$ 100,000	
	4	Update or replace guidance for considering climate change within fluvial flood assessments within "Legislated Flood Assessments in a Changing Climate in BC" (EGBC, 2018).	$ 150,000	
	5	Update or replace guidance for considering climate change within pluvial flood assessments within "Legislated Flood Assessments in a Changing Climate in BC" (EGBC, 2018).	$ 100,000	
	6	Update sea level rise information in "Climate Change Adaption Guidelines for Sea Dikes and Coastal Flood Hazard Land Use: Guidelines for Management of Coastal Flood Hazard Land Use" (Ausenco Sandwell, 2018).	$ 150,000	
	7	Develop Provincial climate change guidance that parallels and clarifies commentary provided in (Engineers & Geoscientists British Columbia, 2018)	$ 200,000	
Total			$ 2,770,000	$ 1,410,000 /yr

BIBLIOGRAPHY

(NHC), N. H. (March 2020). *Okanagan Mainstem Floodplain Mapping.*

AECOM. (2015). *Captial Regional District Coastal Sea Level Rise Risk Assessment*.

Arora, V. K., & Cannon, A. J. (2018). A brief background on climate models: the source of future climate information. *1st International Conference on New Horizons in Green Civil Engineernig*, (pp. 99-107). Victoria, BC.

Associated Engineering. (2019). *Technical review of precipitation projection tool IDF-CC.* Associated Engineering Technical Development Committee.

Associated Engineering. (2019). The Flood Risk Continuum: From Pluvial to Fluvial. *Canadian Water Resources Association.* Collingwood, Ont.

Associated Engineering. (2020). *Coastal Flood Modelling and Mapping Report: Capital Region Coastal Flood Inundation Mapping Project.*

Ausenco Sandwell. (2011a). *Climate Change Adaption Guidelines for Sea Dikes and Coastal Flood Hazard Land Use: Guidelines for Management of Coastal Flood Hazard Land Use.*

Ausenco Sandwell. (2011a). *Climate Change Adaption Guidelines for Sea Dikes and Coastal Flood Hazard Land Use: Guidelines for Management of Coastal Flood Hazard Land Use.*

Ausenco Sandwell. (2011a). *Climate Change Adaption Guidelines for Sea Dikes and Coastal Flood Hazard Land Use: Guidelines for Management of Coastal Flood Hazard Land Use.*

Ausenco Sandwell. (2011b). *Climate Change Adaption Guidelines for Sea Dikes and Coastal Flood Hazard Land Use: Draft Policy Discussion Paper.*

Ausenco Sandwell. (2011b). *Climate Change Adaption Guidelines for Sea Dikes and Coastal Flood Hazard Land Use: Draft Policy Discussion Paper.*

B.C Agriculture and Food Climate Action Initiative. (2014). *Potential economic & agricultural production impacts of climate chagne related fooding in the Fraser delta.* B.C Agriculture and Food Climate Action Initiative.

BC Ministry of Environment. (2011). *Climate Change Adaption Guidelines for Sea Dikes and Coastal Flood Hazard Land Use: Guidelines for Management of Coastal Flood Hazard Land Use.*

BC Ministry of Forests, Lands and Natural Resource Operations. (2014). *Simulating the Effects of Sea Level Rise and Climate Change on Fraser River Scenarios.*

Bornhold, B. (2008). *Projected Sea Level Changes for British Columbia in the 21st Century*.

California Legislature. (2019). *Assembly Bill No. 557*. Retrieved from California Legislative Information: https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201920200AB557

Cannon, A. (2020, June). Investigation B-1 Interview. (J. Fyke, J. van der Eerden, & L. Bird, Interviewers)

City of Vancouver. (2020, June). *City of Vancouver Adaptation Strategy: Sea Level Rise*. Retrieved from City of Vancouver corporate website: https://vancouver.ca/green-vancouver/sea-level-rise.aspx

Compass Resource Management, Ltd. (2016). *City of Vancouver Coastal Flood Risk Assessment Phase 2*.

Coordinated Regional Climate Downscaling Experiment. (2020, June 18). *CORDEX*. Retrieved from CORDEX North America: https://na-cordex.org/

CSA Group. (2018). *CSA PLUS 4013: Technical guide: Development, interpretation and use of rainfall intensity-duration-frequency (IDF) information: Guideline for Canadian water resources practitioners.* Standards Council of Canada.

CSA Group. (2019). *Development, interpretation, and use of rainfall intensity-duration-frequency (IDF) information: Guidelines for Canadian water resources practitioners.* Toronto: CSA Group.

Curry, C., Islam, S., Zwiers, F., & Dery, S. (2019). Atmospheric rivers increase future flood risk in Western Canada's largest Pacific river. *Geophysical Research Letters*.

Dery, S., Sharma, A., & Islam, S. (2020, June). Investigation B-1 Interview. (J. Fyke, & J. van der Eerden, Interviewers)

Deser, C., Knutti, R., Solomon, S., & Phillips, A. (2012). Communication of the role of natural variability in future North American climate. *Nature Climate Chang*, 775-779.

EGBC. (2018). *Legislated Flood Assessments in a Changing Climate in BC.* Engineers & Geoscientists British Columbia.

Environment and Climate Change Canada. (2018, October 12). *The Canadian Regional Climate Model Large Ensemble*. Retrieved from Open Government Portal: https://open.canada.ca/data/en/dataset/83aa1b18-6616-405e-9bce-af7ef8c2031c

Environment and Climate Change Canada. (2019). *Canada' Changing Climate Report: Chapter 6: Changes in Freshwater Availability Across Canada.* Government of Canada.

Environment and Climate Change Canada. (2019). *Canada's Changing Climate Report: Chapter 4: Changes in Temperature and Precipitation Across Canada.* Government of Canada.

Espinoza, V. (2018). *Global Analysis of Climate Change Projection Effects on Atmospheric Rivers.* American Geophysical Union.

European Centre for Medium Range Weather Forecasts. (2020, June). *ERA5: Data Documentation* . Retrieved from European Centre for Medium Range Weather Forecasts: https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5

Eyring, V., Bony, S., Meehl, G., Senior, C., Stevens, B., Stouffer, R., & Taylor, K. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, 1937-2016.

Flood Safety Section Ministry of Forests Lands and Natural Resource Operations, Province of BC. (2015). *Simulating the Effects of Climate Change on Fraser River Flood Scenarios – Phase 2*.

Fyke, J., & Matthews, D. (2015). A probabilistic analysis of cumulative carbon emissions and long-term planetary warming. *Environmental Research Letters*.

Fyke, J., Sergienko, O., Lofverstrom, M., Price, S., & Lenaerts, J. (2018). An overview of interactions and feedbacks between ice sheets and the Earth system. *Reviews of Geophysics*.

Hausfather, Z., & Peters, G. (2020). Emissions - the 'business as usual' story is misleading. *Nature*.

Hazeleger, W., van den Hurk, B., Min, E., Jan Van Oldenborgh, G., Petersen, A., Stainforth, D., . . . Smith, L. (2015). Tales of future weather. *Nature Climate Change*.

Hu, A., & Bates, S. (2018). Internal climate variability and projected future regional steric and dynamic sea level rise. *Nature Communications*.

Huard, D. (2020, June). Investigation B-1 Interview. (J. Fyke, J. van der Eerden, & L. Bird, Interviewers)

Intergovernmental Panel on Climate Change. (2018, July 19). *IPCC AR6 WGI Schedule.* Retrieved from Sixth Assessment Report (AR6): https://wg1.ipcc.ch/docs/AR6_WGI_Schedule.pdf

James, T. (2020, June). Investigation B-1 Interview. (J. Fyke, & L. Bird, Interviewers)

James, T. S., & et al. (2014). *Relative Sea-level Projections in Canada and the Adjacent Mainland United States.* Geologic Survey of Canada.

James, T., Henton, J. A., Leonard, L. J., Darlington, A., Forbes, D. L., & Craymer, M. (2014). *Relative Sea-level Projections in Canada and the Adjacent Mainland United States.* Geologic Survey of Canada.

James, T., Robin, C., Henton, J., & Craymer, M. (in preparation). *Open file; Relative sea-level projections for Canada's coastlines.* Geologic Survey of Canada.

Jost, G. (2020, June). Investigation B-1 Interview. (J. Fyke, J. van der Eerden, & L. Bird, Interviewers)

Khaliq, N. (2019). *An inventory of methods for estimating climate change-informed design water levels for floodplain mapping.* National Research Council.

Khaliq, N. (2020, June). Investigation B-1 Interview. (J. Fyke, J. van der Eerden, & L. Bird, Interviewers)

Kopp, R., Hay, C., Little, C., & Mitrovica, J. (2015). Geographic variability of sea-level change. *Current Climate Change Reports*, 192-204.

Lawrence, D., Hurtt, G., Arneth, A., Brovkin, V., Calvin, K., Jones, A., . . . Shevliakova, E. (2016). The Land Use Model Intercomparison Project (LUMIP) contribution to CMIP6: rationale and experimental design. *Geoscientific Model Development*, 2973–2998.

Li, C., Zwiers, F., Zhang, X., Chen, G., Lu, J., Li, G., . . . Liu, M. (2019). Larger increases in more extreme local precipitation events as climate warms. *Geophysical Research Letters*, 6885-6891.

Lindenschmidt, K.-E., Das, A., Rokaya, P., & Chu, T. (2016). Ice-jam flood risk assessment and planning. *Hydrological Processes*, 3754-3769.

Ludwin, R., Dennis, R., Carver, D., McMillan, A., Lose, R., Clague, J., . . . James, K. (2005). Dating the 1700 Cascadia earthquake: great coastal earthquakes in native stories. *Seismological Research Letters*.

Lyle, T., & Hund, S. (2020, June). Investigation B-1 Interview. (J. Fyke, & J. van der Eerden, Interviewers)

MacLatchy, M. (2020, June). Investigation B-1 Interview. (J. Fyke, & J. van der Eerden, Interviewers)

Manson, G., Couture, N., & James, T. (2019). *Geological Survey of Canada Open File 8551: CanCoast 2.0: data and indices to descibe the sensitivity of Canada's marine coasts to changing climate.* Geological Survey of Canada.

Matrix Solutions, Inc. (2018). *Kicking Horse River Climat Change Adaptation: Ice Jamming and Gravel Deposition.* Golden, British Columbia.

Ministry of Environment and Climate Change Strategy. (2019). *Preliminary Strategic Climate Risk Assessment for British Columbia.* Government of British Columbia.

Ministry of Forests, Lands and Natural Resource Operations. (2011). *Coastal Floodplain Mapping - Guidelines and Specifications.*

Ministry of Water, Land and Air Protection, Province of BC. (Amended, 2018). *Flood Hazard Area Land Use Management Guidelines.*

Muis, S., Apecechea, M., Dullaart, J., Rego, J., Madsen, K., Su, J., . . . Verlaan, M. (2020). A high-resolution global dataset of extreme sea levels, tides, and storm surges, Including future projections. *Frontiers in Marine Science: Coastal Ocean Processes*.

Murphy, E. (2020, June). Investigation B-1 Interview. (J. Fyke, & J. van der Eerden, Interviewers)

Musselman, K. N., Lehner, F., Ikeda, K., Clark, M., Prein, A. F., Liu, C., . . . Rasmussen, R. (2018). Projected increases and shifts in rain-on-snow flood risk over western North America. *Nature Climate Change*, 808–812.

Natural Resources Canada, Public Safety Canada. (2018). *Case Studies on Climate Change in Floodplain Mapping.*

Natural Resources Canada, Public Safety Canada. (2019). *Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation.*

Neale, T. (2020, June). Investigation B-1 Interview. (J. Fyke, & J. van der Eerden, Interviewers)

Northwest Hydraulic Consultants. (2009). *Flood risk evaluation and flood control solutions: Phase 1 - Final Report.* Prince George.

Northwest Hydraulic Consultants. (2014). *City of Vancouver Coastal Flood Risk Assessment.*

Nowicki, S., Payne, A., Larour, E., Seroussi, H., Goelzer, H., Lipscomb, W., . . . Shepherd, A. (2016). Ice Sheet Model Intercomparison Project (ISMIP6) contribution to CMIP6. *Geoscientific Model Development*.

Oulahen, G., Klein, Y., Mortsch, L., O-Connell, E., & Harford, D. (2018). Barriers and drivers of planning for climate change adaptation across three levels of government in Canada. *Planning Theory and Practice*, 405-421.

Pacific Climate Impacts Consortium. (2020, June 6). *Pacific Climate Impacts Consortium Data Portal*. Retrieved from Gridded Hydrologic Model Output: https://www.pacificclimate.org/data/gridded-hydrologic-model-output

Payne, A., Demory, M.-E., Leung, R. L., Ramos, A., Shields, C., Rutz, J., . . . Ralph, M. (2020). Responses and impacts of atmospheric rivers to climate change. *Nature Reviews*.

Picketts, I., & Dyer, D. (2012). *Implementing climate change adaptation in Prince George, BC: Volume 4: Flooding.* Prince George.

Pinna Sustainability. (2014). *The future of atmospheric rivers and actions to reduce impacts to British Columbians.*

Prein, A. (2020). *Increased melting level height impacts surface precipitation phase and intensity*.

Province of Alberta. (2018). *Ice Jam Flooding*. Province of Alberta.

Province of British Columbia. (2018). *Amendment Sections 3.5 and 3.6 "Flood Hazard Area Land Use Management Guidelines"* . Province of British Columbia.

Province of British Columbia. (2020, June 6). *Climage Change Indicators*. Retrieved from Environmental Reporting BC: https://www2.gov.bc.ca/gov/content/environment/research-monitoring-reporting/reporting/environmental-reporting-bc/climate-change-indicators

Province of British Columbia. (2020, June 6). *Climate Change Indicators*. Retrieved June 6, 2020, from Environmental Reporting BC: https://www2.gov.bc.ca/gov/content/environment/research-monitoring-reporting/reporting/environmental-reporting-bc/climate-change-indicators

Raftery, A., Zimmer, A., Frierson, D., Startz, R., & Liu, P. (2017). Less than 2C warming by 2100 unlikely. *Nature Climate Change*, 637-641.

Robin, C. (in preparation). Geologic Survey of Canada.

Rokaya, P., Budhathoki, S., & Lindenschmidt, K.-E. (2018). Trends in the timing and magnitude of ice jam floods in Canada. *Nature Sientific Reports*, 1-9.

Sharma, A. R., & Dery, S. (2020). Contribution of atmospheric rivers to annual, seasonal and extreme precipitation across British Columbia and Southeastern Alaska. *Journal of Geophysical Research*.

Sharma, A., & Dery, S. (2020). Variability and trends of landfalling atmospheric rivers along the Pacific Coast of northwestern North America. *International Journal of Climatology*, 544-558.

Shields, C., Rutz, J., Leung, R., Ralph, M., Wehner, M., O'Brien, T., & Pierce, R. (2019). Defining uncertainties through comparison of atmospheric river tracking methods. *Bull. Amer. Meteor. Soc.*, ES93-ES-96.

Shoeneberg, A. (2020, July). Investigation B-1 Interview. (J. Fyke, & J. van der Eerden, Interviewers)

Shrestha, R. (2020, June). Investigation B-1 Interview. (J. Fyke, J. van der Eerden, & L. Bird, Interviewers)

Simonovic, S., Schardong, A., Gaur, A., & Sandink, D. (2020, JUne). *Computerized Tool for the Development of Intensity-Duration-Frequency Curves under Climate Change – Version 4.0*. Retrieved from Computerized Tool for the Development of Intensity-Duration-Frequency Curves under Climate Change – Version 4.0: https://www.idf-cc-uwo.ca/

Swart, N., Cole, J., Kharin, V., Lazare, M., Scinocca, J., Gillet, N., . . . Winter, B. (2019). The Canadian Earth System Model version 5 (CanESM5.0.3). *Geoscientific Model Development*, 4823-4873.

The Arlington Group Planning + Architecture Inc. (2013). *Sea Level Rise Adaptation Primer: A Toolkit to Build Adaptive Capacity on Canada's South Coasts*. British Columbia Ministry of Environment.

Transport Canada. (2020, June). *Transportation Assets Risk Assessment (TARA) Program*. Retrieved from Transport Canada Programs: https://www.tc.gc.ca/en/programs-policies/programs/transportation-assets-risk-assessment-program.html

Turcotte, B. (2020, June). Issue B-1 Interview. (J. Fyke, & J. van der Eerden, Interviewers)

Turcotte, B., & Morse, B. (2015). River ice breakup forecast and annual risk distribution in a climate change perspective. *18th Workshop on the Hydraulics of Ice Covered Rivers* . Ottawa: CGU HS Committee on River Ice Processes and the Environment.

Turcotte, B., Burrell, B., & Beltaos, S. (2019). The Impact of Climate Change on Breakup Ice Jams in Canada: State of knowledge and research approaches. *20th Workshop on the Hydraulics of Ice Covered Rivers.* Ottawa: Canadian Geophysical Union HS Committee on River Ice Processes and the Environment.

U.S. Global Change Research Program. (2017). *Fourth National Climate Assessment (NCA4), Volume I.*

UK Meteorological Office. (2020, June 25). *UK Climate Projections*. Retrieved from https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/index

United Nations Intergovernmental Panel on Climate Change. (2009). *The Copenhagen Diagnosis, 2009: Updating the World on the Latest Climate Science.* United Nations.

United Nations Intergovernmental Panel on Climate Change. (2013). *Assessment Report 5: Chapter 13: Sea Level Rise.* United Nations.

United Nations Intergovernmental Panel on Climate Change. (2019). *Special Report on the Ocean and Cryosphere in a Changing Climate.* United Nations.

Werner, A., Schnorbus, M., Shrestha, R., Cannon, A., Zwiers, F., Dayon, G., & Anslow, F. (2019). A long-term, temporally consistent, gridded daily meteorological dataset for northwest North America. *Nature Scientific Data*.

World Meteorological Organization. (2017). WMO guidelines on the calculation of climate normals. WMO-No. 1203.

Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R., . . . Vignotto, E. (2020). A typology of compound weather and climate events. *Nature Reviews Earth and Environment*, 333-347.

Zscheischler, J., Westra, S., van den Hurk, B., Seneviratne, S., Ward, P., Pitman, A., . . . Zhang, X. (2018). Future climate risk from compound events. *Nature Climate Change*.

APPENDIX A – CLIMATE MODELS, ENSEMBLES, DOWNSCALING, BIAS CORRECTION AND IMPACT MODELLING

Global climate models (GCMs, also called Earth System Models or ESMs) are computer programs that represent all important global climate system components (ocean, atmosphere, land, sea ice, hydrology, and biological and chemical cycles). These components are represented based on general principles of fluid dynamics, thermodynamics, chemistry, biological interactions, as represented in the computer code that forms the basis for GCMs (Arora & Cannon, 2018). When GCMs are provided with estimates of past and future greenhouse gas emissions or concentrations (e.g. derived from observations or estimated via future climate scenarios, such as the Representative Concentration Pathway or RCP scenarios, Appendix B) they produce estimates of past and future changes to key environmental variables such as temperature, precipitation, wind, permafrost, snow, and sea level.

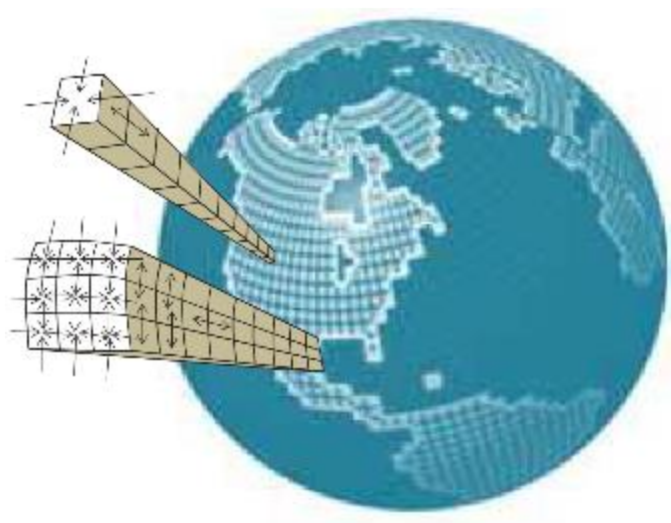


Figure A-1
Global Climate Model Schematic

Figure from (Arora & Cannon, 2018)

GCM simulations are typically very computationally expensive, meaning that only a limited number of simulations are possible for targeted future climate, with simulations performed on large supercomputers. The results of these simulations (e.g. model-based estimates of past and future change) display very similar fundamental characteristics of actual climate and weather observations. For example, climate model simulations include output datasets of temperature, precipitation, wind speed and direction, at any location on the planet, for any day of any year – including both years in the past, and years in the future.

Because of the face-value similarity between climate model output and real-world observations, it is tempting to assume that the former can in principle be swapped one-for-one with the latter. However, extra care is warranted when using GCM-produced simulated climate and weather information (Arora & Cannon, 2018). For example:

- Because of climate model simulation design and the nature of short-term weather and climate conditions (Arora & Cannon, 2018), absolute timing of specific climate events (particularly, individual extreme events that cause provincial flooding) differs between historical GCM simulations and the real world. Comparisons between GCM output and observations thus must take the form of comparisons between climate and observed weather statistics, instead of comparison of individual events, at the same point in time and space. For example, a 'good' GCM simulation is one in which the distribution of daily seasonal precipitation compares well to observations, over sufficiently long periods, such as the standard 30-year climate 'normal' period (World Meteorological Organization, 2017).
- Natural climate variability or 'noise' is large at local scales (for example, as measured by a single weather station, or at a single GCM grid cell location). This noise can often overwhelm the underlying climate change trend, leading to the potential risk of confusing one for the other. Spatial averaging (the use of values

generated by averaging across multiple GCM grid cells) can avoid this pitfall – for example, by averaging projected precipitation values across the entire province, and across multiple climate model simulations within a larger ensemble (see following discussion).

- GCM-produced climate and weather data is not directly observationally sourced. Rather, it is generated by computer code that represents key processes in the global climate system. For this reason, it may have significant biases relative to actual local observations, since it is impossible to constrain GCM simulations to fall within the bounds of observations, at all global points and all historical times.
- GCMs strive to include all key aspects of the climate system at an adequate resolution, given computational constraints. However, it is impossible to account for every last climate process (for example, each raindrop, soil grain, or ocean wave, let alone provincial convective storm events. As a result, many processes are simplified via 'parameterizations' that attempt to consider the bulk behaviour of a particular system. Ramifications and consequences of these simplifications on final model output values needs to be understood, if the resulting output is used for real-world flood planning at the provincial level.
- For technical reasons, GCMs currently still do not include processes that are known to be important in the context of climate change impacts to provincial flooding. As one prominent example, the Antarctic Ice Sheet, containing the largest reservoir of global sea level rise potential on the planet (~58m) is not yet included in any operational GCMs, due to large challenges in simulating Antarctic ice dynamics and coupling to surrounding oceans. As a result, provincial sea level rise estimates generated solely from GCM simulations exclude what is perhaps the largest future contributor to provincial sea level rise. This example highlights the need for GCM data use to be coordinated with an objective assessment of GCM design, including evaluation of structural model deficiencies and/or entirely absent model components.

Climate model ensembles are large, coordinated sets of individual climate model simulations, that can be used to develop broader understanding of projected climate change trend magnitudes, as well as uncertainties in these projections. There are a number of different types of ensembles, that are designed with various purposes in mind. However, three primary types of ensembles are particularly important to understand in the context of integrating future climate change into provincial flood planning. These are:

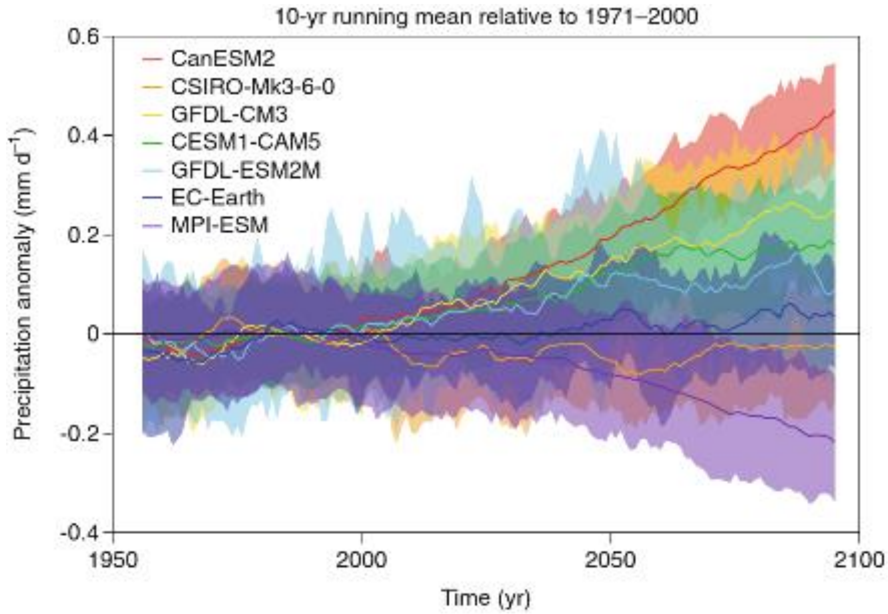


Figure A-2
Example of Multi-Model Output Demonstrating Range of Future Projections Due to Model Uncertainty (in This Case, Annual Precipitation Anomalies for the Upper Colorado River Basin). Thick Lines: Model-Specific Results Calculated as Average of Individual Single-Model Perturbed-Initial-Conditions Ensembles

Image: (Deser, Lehner, Rodgers, & et al., 2020).

- Multi-GCM ensembles using a similar emission scenario: different GCMs, forced with the same historical/future emission scenario and related constraints Figure A-2. These ensembles provide a means to assess the range of potential future climate projections resulting from different GCM designs. A key case study of this ensemble type is the CMIP6 project (Eyring, et al., 2016), which coordinates worldwide GCM simulations for clearly defined 'families' of simulations. Similar multi-GCM approaches are also taken for regional modelling/dynamical downscaling efforts, as described below (Coordinated Regional Climate Downscaling Experiment, 2020).
- Single-model ensembles using different emission scenarios: These ensembles provide a means to assess the range of future climate conditions resulting from the range of plausible emission and land use changes over the 21st century (Figure A-3). A key case study of this ensemble type are GCM-specific sets of simulations (e.g. CanESM simulations) across multiple RCP scenarios.
- Single-model perturbed initial condition ensembles of the same climate scenario: These ensembles provide a means to assess the range of conditions that may be expected at any time during the past or future, due to natural climate variability or 'noise'. They also allow for improved estimates of the climate change signal that underlies this noise. Figure A-2 and Figure A-3 both demonstrate this type of ensemble, with the thick lines in both cases highlighting ensemble-average conditions along particular climate scenarios, with shading and/or thin lines indicating the spread due to natural climate variability.

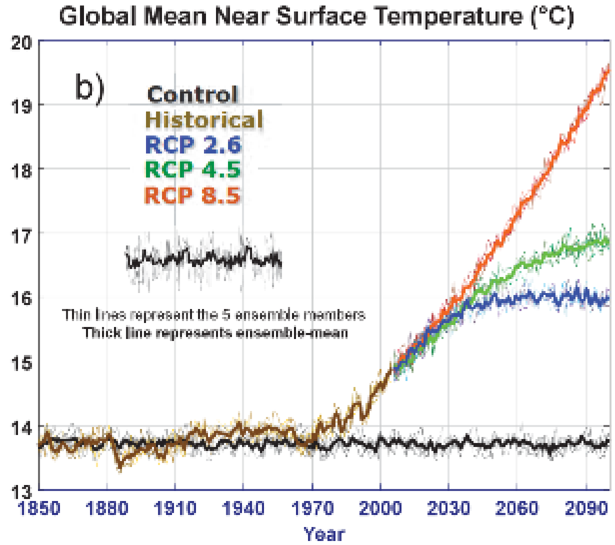


Figure A-3
Example of a Single-Model Output Ensemble Containing Simulations Across RCP Scenarios, and Using Multiple Perturbed-Initial-Condition Model Simulations. Model: CanESM2.
Image: (Arora & Cannon, 2018)

Downscaling can occur via one or a combination of two general methods:

- Dynamical downscaling: in which high resolution regional climate models are forced with GCM historical and future simulation data, to improve resolution of conditions at regional and local scales. Dynamic downscaling explicitly captures climate and weather dynamics at smaller scales, albeit at the cost of additional computing requirements. Due to increased model complexity, dynamic downscaling can also introduce additional biases in the course of improving the spatial fidelity of regional climate data. Examples of dynamical downscaling are the use of the regional climate model CanRCM4 to downscale CanESM2 global model results to ~40 km resolution (Environment and Climate Change Canada, 2018), and outputs of the CORDEX project over North America, including B.C. (Coordinated Regional Climate Downscaling Experiment, 2020).
- Statistical downscaling: in which local information (for example, meteorological station data and topography) is used to develop relationships between GCM output and local changes. Statistical downscaling benefits from relatively low computational cost (although it can still take significant computer resources to carry out at scale). On the other hand, it is inherently tied to statistics relating model results and observations, that are derived from the present-day climate system. These statistics (particularly, around extreme storm events) may

not hold in the case of significantly changed future conditions. An example of a statistical downscaled product is the widely-disseminated BCCAQ V2 dataset produced by the Pacific Climate Impact Consortium (Pacific Climate Impacts Consortium, 2020).

Bias correction is often closely associated with downscaling and is intended to account and correct for the bias that can be measured between GCM simulated results and real-world observations. A wide range of bias correction methods exist and can have significant impacts on correct and downscaled data. As a few examples:

- Bias correction is by necessity based on distributions differences between historical GCM simulations and observations. This difference may not apply in the case of significantly changed future climate conditions.
- Bias correction methods that apply simple 'delta' approaches may produce incorrect results, when applied to changes in extreme climate events (e.g. those events associated with provincial flooding).
- Bias correction methods that attempt to reduce bias through analog techniques (e.g. the commonly-used BCCAQ V2 dataset produced by the Pacific Climate Impact Consortium (Pacific Climate Impacts Consortium, 2020)) can produce randomized versions of internal variability that lose the signal of persistent, coherent, multi-day events (e.g. multi-day atmospheric river or rain-on-snow events).

For more general information on GCMs, downscaling and bias correction in the Canadian context, the reader is encouraged to refer to (Arora & Cannon, 2018) and related overviews of GCMs. For further discussion of downscaling and bias correction in the context of Canadian floodplain mapping efforts, the reader is encouraged to refer to (Khaliq, Report No.: NRC-OCRE-2019-Tr-011, 2019).

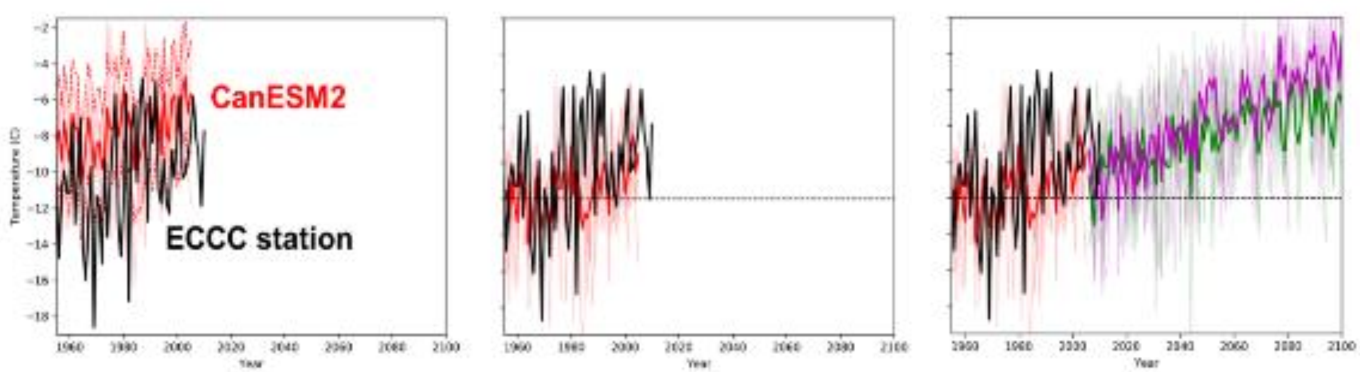


Figure A-4
Example Schematic of Bias Correction Process, Involving Simple Identification (leftmost panel) and Removal (middle panel) of a Wintertime Warm Bias in CanESM2 Climate, Followed by Bias-Corrected Future Simulations (rightmost panel, purple/green traces).

Impact modelling refers to the use of specialized models or analyses to translate meteorological data produced by GCMs and/or downscaling, into information that can be directly applied to decision making. Impact models are process specific. In the case of assessments of provincial flooding, impact models can include:

- Watershed-scale and province-scale hydrologic models that translate meteorological information into streamflow hydrographs.

- Hydraulic models that translate streamflow volume fluxes to flood heights, or pluvial flood fluxes into inundation depths.
- Coastal oceanographic models that translate global sea level and marine meteorological information into local sea level, and storm waves and surges.
- Ice jam models that translate regional hydrology, meteorology and river geometries into local-scale river ice jam build-up/break-up dynamics

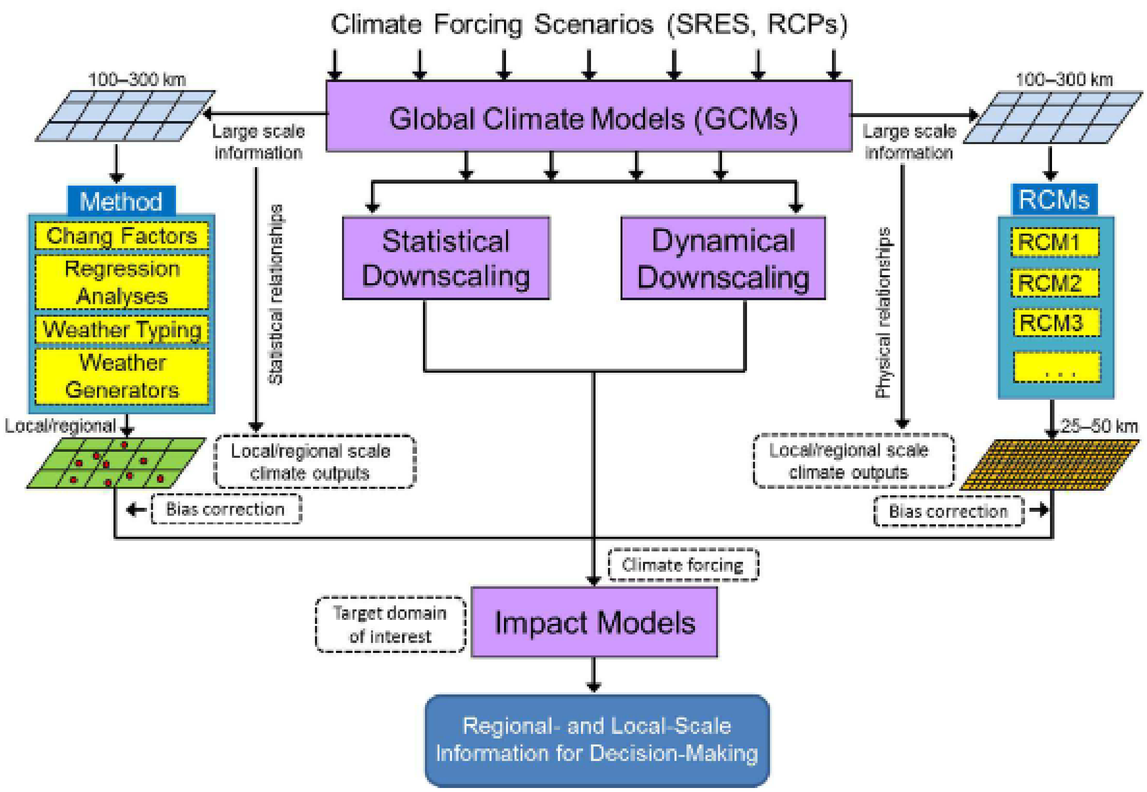


Figure A-5
Schematic Indicating the Role of Impact Modelling in Translating Meteorological Information from Climate Modelling and Downscaling/Bias Correction, into Information That Can Be Used for Decision-Making. Impact Models Can Take Many Forms and Are Process Specific.
Image: (Khaliq, Report No.: NRC-OCRE-2019-Tr-011, 2019)

A common feature of all impact models is that they have the capacity to ingest primarily meteorological data (either derived from climate model sources, or direct observations), and in turn, output flood metrics that can be directly utilized by flood planning efforts. In many respects, impact models have close conceptual similarities to climate models (and indeed, any model of a real-world system). For example, all impact models are by necessity simplifications of real-world systems (for example, individual rivers, or ice jam events). Impact models can also be used in an ensemble setting, to develop a better understanding of system behaviour and future change. For example, hydrologic models have long been used in ensemble mode to probabilistically forecast near-term river levels – and this same conceptual approach could be adopted in the context of longer-term projections of flood response to climate change (Jost, 2020).

APPENDIX B – FUTURE CLIMATE SCENARIOS

To address future climate change uncertainty related to uncertainty in future human behaviour, 'representative' greenhouse gas emissions scenarios can be constructed from Integrated Assessment Models (IAMs). Like GCMs, IAMs are computer programs that, using codified social, economic, and environmental relationships, explore how human development and societal choices interact with the natural world to generate greenhouse gas emissions, and concentrations, land use changes, and other key, climate-relevant outputs. IAMs includes physical laws driving natural systems, as well as the changing habits and preferences that drive human society. Importantly, future greenhouse gas concentration projections from IAMs are used to force GCM simulations that project future climate change magnitudes (Appendix B). As such, IAMs are a critical (though typically poorly understood) part of the overall tool chain that guides provincial flood planning in consideration of climate change.

IAM-generated scenarios can estimate global greenhouse gas emissions/concentrations that are consistent with a wide set of potential future socioeconomic trends. Since the 1990s, three major 'families' of emission scenarios have been generated, with the latest being the Representative Concentration Pathways (RCPs). Each main RCP scenario captures a potential 21st century emissions future:

- RCP 2.6 is a low emissions scenario that assumes near-term, strong emissions reductions and near-complete cessation of greenhouse gas emissions by ~2050.
- RCP 4.5 is a low-intermediate emissions scenario in which global emissions peak and begin to decline by ~2035.
- RCP 6.0 is a high-intermediate emissions scenario, in which global emissions peak and begin to decline by ~2060.
- RCP 8.5 is a high emissions scenario that combines high population growth with continued fossil fuel use – particularly coal – through to year 2100.

Projected impacts to flooding vary in direct relation to the underlying emissions scenarios. For example, RCP 2.6 climate projections (e.g. climate model simulations forced with RCP 2.6 greenhouse gas emissions) represent an optimistic scenario in which climate change impacts to provincial floods are low because of drastic, near-future reductions in global greenhouse gas emissions. RCP 4.5 and RCP 6.0 climate projections represent plausible intermediate impact scenarios, while RCP 8.5 climate projections represent an upper bound of expected climate change impacts to provincial flooding.

No RCP scenario is associated with a likelihood. As a result, users of RCP-based climate projection information must make what can be a challenging, risk-based decision regarding which scenario to apply to flood planning assessment efforts. Some factors to consider in this decision-making include the following:

- RCP 2.6 is likely an unrealistically optimistic scenario (Raftery, Zimmer, Frierson, Startz, & Liu, 2017).
- RCP 8.5 is likely an unrealistically pessimistic scenario (Hausfather & Peters, 2020) (James T. , 2020).
- RCP 4.5 and RCP 6.0 represent more-likely scenarios (Fyke & Matthews, 2015).

RCP scenarios of change are relatively similar until ~2050, after which they diverge (Figure A-2).

APPENDIX C – INVESTIGATION METHODS

Issue B-1 focussed on documenting 1) the state-of-the-art in provincial and regional understanding, related to climate change influences on floods; and 2) current integration of climate change considerations into actual flood planning. The approach taken involved a combination of semi-structured, in-depth interviews, and review of existing documents (Bibliography).

Individuals at the forefront of climate change integration into flood science, policy and planning are not widespread, and often operate in very specific, technical roles. For this reason, the project team determined that the best approach for documenting this state of knowledge was individual interviews with subject matter experts.

The procedure for conducting interviews was as follows:

- Potential interviewees were identified via:
  - Professional networks.
  - Authorship of prominent analyses or reports on the topic of regional climate change/flood impacts.
  - Technical leadership positions in relevant provincial, national, or international organizations.
  - Prominent policy or leadership positions in government.
- Interviewees were contacted with a formal invitation letter to participate in an approximately ½ hour-long interview, held via Skype for Business, phone call, or other suitable mechanism.
- Interviewees willing to be interviewed received confirmation appointments. 100% of potential interviewees agreed to be interviewed.
- During the interview:
  - Audio recordings were taken, with a few exceptions due to technical difficulties.
  - Associated team interviewers also recorded notes.
- After the interview:
  - Audio and note files were collated into a common internal network directory.
  - Follow-up as appropriate was facilitated by subsequent emails or phone calls.

During initial outreach communications, a set of questions was provided to interviewees, with tailoring according to interviewee discipline expertise. However, similar to the approach taken by (Oulahen, Klein, Mortsch, O-Connell, & Harford, 2018), interviewees were encouraged to expand on topics related to climate change integration into flood science/policy/planning, that they felt were most appropriate. As a result, in almost all cases, the discussion diverged significantly from the pre-planned questioning schedule. Using this approach, several primary interview goals, below, were attained:

- To understand the roles/responsibilities of interviewee;
- To understand how climate change considerations are being integrated into interviewee's flood-related professional work;
- To understand key advances being performed by interviewee (or interviewee's organization);

- To understand what technical, programmatic, communication, and other, opportunities and challenges the interviewee faces, in integrating climate change into flood-related professional work;
- To document key priorities for interviewees, related to integrating climate change into flood-related professional work; and,
- To document other professionals the interviewee believes the AE project team should contact, using a network-of-networks approach.

These goals ensured that interviews produced relevant information and context and provided confidence that the project team was not missing any potentially relevant interviewees.

A wide range of reports and studies were reviewed as part of this investigation (Bibliography Section). These reports were identified in multiple ways, including personal Author knowledge, references provided by project interviewees, targeted web searches, and documents referenced in previously identified documents. In many cases, reviewed documents were only partially related to climate change impacts. In these cases, a text string search was performed to efficiently identify relevant document sections for review. Searched text strings to identify relevant sections included:

- “Climate”
- “Climate change”
- “Climate model”
- “Future projection”
- “Downscaled”/”downscaling”

Ground-truthing these search strings against known documents was employed to verify the ability of these text string searches to extract content relevant to Issue B1 from larger documents.

APPENDIX D – SUMMARY OF DETAILED AND SPECIFIC RECOMMENDATIONS

Summary of Detailed and Specific Recommendations from Report Call-Out Boxes

Investigation	Report Section	Recommendation
B-1.2	2.2.1	Monitor GCM development for direct hydrology simulations of sufficient quality and resolution for local-scale freshet flood assessments.
B-1.2	2.2.1	Monitor CMIP6 progress for GCM model output and derivative products that are mature enough for application to freshet-focussed hydrological assessments.
B-1.2	2.2.2	Increase the density of remote and mid-high elevation climate monitoring stations and snow courses throughout B.C.
B-1.2	2.2.3	Calibrate hydrologic models that are to be used for future projections using historical climate model data, rather than direct observations.
B-1.2	2.2.3	Develop and distribute province-wide downscaled climate datasets at daily or subdaily resolution.
B-1.2	3.2.2	Strengthen provincial multivariate statistical downscaling and regional modelling research efforts in support of atmospheric river projections.
B-1.2	4.2.1	Complete a risk assessment and prioritize development of location-specific assessments of climate change impacts to ice jam flooding
B-1.2	4.2.2	Increase observations of wintertime hydrologic and meteorological conditions where provincial ice jam flooding occurs.
B-1.2	5.2.1	Regularly monitor developments in sea level rise science and projections from national and international research centres.
B-1.2	5.2.1	Encourage local, regional and First Nation governments to complete regional coastal flood hazard assessments for a range of RSLR scenarios to facilitate risk-based approaches and to allow for adaptive management.
B-1.2	5.2.1	Adopt emerging, regional datasets of changes to B.C. coastal waves and storm surges such as developed in “Transportation Assets Risk Assessment (TARA) Program” (Transport Canada, 2020) as part of coastal flood planning.
B-1.2	5.2.2	Adopt emerging, spatially complete datasets of B.C. relative sea level rise (James, Robin, Henton, & Craymer, in preparation) as part of coastal flood planning.
B-1.2	6.2.2	Develop operational high-resolution regional climate models of B.C. to better understand climate change impacts to extreme precipitation and pluvial floods.
B-1.2	7.1	Develop spatial/temporal patterns of flood types under present/future climate conditions and assess overlap regions where compound event flooding may increase in future.
B-1.3	2.2.2	Support technical training for hydrologists and flood hazard specialists to better understand downscaling methods and application of downscaled data.
B-1.3	3.2.1	Support basic research to better constrain the link between climate change, atmospheric rivers, and peak flooding.
B-1.3	8.1	Provide ongoing educational and training opportunities for local, regional and First Nation governments to provide a consistent understanding of the impacts of climate change on flood hazard.
B-1.3	8.2	Support Provincial capacity to assess climate change impacts to atmospheric rivers possibly mirroring the approach taken by the State of California.
B-1.3	8.3	Increase support for Provincial capacity to assess climate change impacts to ice jam flooding, that potentially mirrors the approach taken by the Province of Alberta.
B-1.3	8.5	Establish Provincial guidance and technical training for methods of developing short-duration extreme precipitation projections that would be suitable to use in industry supported impact models.
B-1.3	8.7	Develop a formal collaboration network of subject matter experts (SME's) that would support development of guidance documentation related to application of emission pathways, climate model selection, time horizons and related issues.
B-1.3	8.8	Strengthen existing provincial downscaling and climate change/flood impact modelling capacity.
B-1.3	8.8	Develop and support a provincial flood hazard assessment practitioner collaboration network that spans local, First Nation and regional governments and private sector consultants.
B-1.3	8.8	Develop literacy training for the public, related to climate change impacts to floods.
B-1.3	8.8	Develop literacy training for local government representatives, related to climate change impacts to floods.
B-1.3	8.8	Develop and support technical capacity training for provincial practitioners to integrate climate change trends into flood planning.
B-1.3	8.8	Incentivize provincial academic researchers to develop practitioner-relevant academic research.
B-1.4	2.2.1	Develop Provincial standards for using ensemble-based approaches to calculate future design flood statistics and highlight project examples of where these approaches have been applied successfully.
B-1.4	2.2.3	Develop Provincial hydrologic modelling approaches that effectively represent freshet-based flooding in a changing climate by potentially building upon existing frameworks such as RFC's CLEVER.
B-1.4	3.2.3	Develop hydrologic modelling guidelines specifically targeted, calibrated, and validated, to represent atmospheric river-based flooding.
B-1.4	6.1	Develop technical guidance for practitioners, on understanding the full spectrum of pluvial events from convective storms to atmospheric rivers
B-1.4	8.2	Update “The Future of Atmospheric Rivers and Actions to Reduce Impacts to British Columbians” (Pinna Sustainability, 2014) with more recent provincial atmospheric river research findings and related guidance.
B-1.4	8.4	Update Provincial policy, regulations and guidelines related to sea level rise to incorporate emerging B.C.-specific relative sea level rise, and wave/storm surge projections described in this report.
B-1.4	9.1	Update “Legislated Flood Assessments in a Changing Climate in B.C.” (EGBC, 2018) to reflect current climate science and hydrologic understanding of freshet flooding. Base updated recommended methodology on “An Inventory of Methods for Estimating Climate Change-Informed Design Water Levels for Floodplain Mapping” (Khaliq, 2019).
B-1.4	9.2	Update “Legislated Flood Assessments in a Changing Climate in BC” (EGBC, 2018) or superseding guidance to reflect current climate science and hydrologic understanding of atmospheric river flooding. Consult (Khaliq, 2019) on potential methodologies.
B-1.4	9.3	Update “Legislated Flood Assessments in a Changing Climate in BC” (EGBC, 2018) or provide superseding guidance to reflect current climate science and hydrologic understanding of ice jam flooding. Consult “An Inventory of Methods for Estimating Climate Change-Informed Design Water Levels for Floodplain Mapping” (Khaliq, 2019) on possible approaches.
B-1.4	9.4	Update “Legislated Flood Assessments in a Changing Climate in BC” (EGBC, 2018), (Ausenco Sandwell, 2011a), (Ausenco Sandwell, 2011b), and the “Flood Hazard Area Land Use Management Guidelines” (Province of British Columbia, 2018). or superseding guidance to reflect current climate science and sea level understanding of coastal flooding. Consult An inventory of methods for estimating climate change-informed design water levels for floodplain mapping (Khaliq, 2019) on possible methodologies.
B-1.4	9.5	Update “Legislated Flood Assessments in a Changing Climate in BC” (EGBC, 2018) or superseding guidance to reflect current climate science and hydrologic understanding of pluvial flooding. Consult “Development, Interpretation, and Use of Rainfall Intensity-Duration-Frequency (IDF) Information: Guidelines for Canadian Water Resources Practitioners” (CSA Group, 2019) and “An Inventory of Methods for Estimating Climate Change-Informed Design Water Levels for Floodplain Mapping” (Khaliq, 2019) on possible methodologies.
B-1.4	9.5	Update “Legislated Flood Assessments in a Changing Climate in BC” (EGBC, 2018) or develop superseding guidance that sets the minimum standard for urban drainage in a changing climate including developing rainfall statistics and addressing the flood risk continuum posed by compound events that can exacerbate urban flooding.
B-1.4	9.6	Update “Legislated Flood Assessments in a Changing Climate in BC” (EGBC, 2018) or develop superseding guidance to reflect current climate science and hydrologic understanding of compound flooding. Consult “An inventory of methods for estimating climate change-informed design water levels for floodplain mapping” (Khaliq, 2019) for potential methodologies.
B-1.4	9.7	Develop Provincial guidance that parallels and clarifies commentary provided in “Legislated Flood Assessments in a Changing Climate in BC” (EGBC, 2018).

APPENDIX E – LIST OF ALL INVESTIGATIONS

Investigations in Support of Flood Strategy Development in BC

List of All Investigations

Theme A. Governance

Issue	Investigation
A-1 Flood Risk Governance	1. Identify the flood management services provided by each order of government in BC.
	2. Investigate the roles of non-government entities in flood management in BC.
	3. Identify challenges, gaps and limitations with current service delivery.
	4. Identify opportunities for improving collaboration and coordination within and across authorities and adjusting non-government entities' roles that would address challenges and improve efficiency and effectiveness.
	5. Recommend changes to support improved collaboration and coordination in flood management, including an analysis of benefits and costs/limitations for each recommendation.
	6. Investigate alternative options for distributing and integrating flood management responsibilities among authorities, including an analysis of benefits and costs/limitations for each option.

Theme B. Flood Hazard and Risk Management

Issue	Investigation
B-1 Impacts of Climate Change	1. Investigate the state of climate change science in relation to BC flood hazards and identify gaps and limitations in provincial legislation, plans, guidelines and guidebooks related to flood hazard management in a changing climate.
	2. Identify current sources of information and models used by experts in the province to predict future climate impacts and investigate opportunities for improved predictive modeling.
	3. Investigate the capacity of responsible authorities and other professionals and practitioners in the province to integrate climate change impacts and scenarios to inform flood planning and management.
	4. Investigate the legislative, policy, and regulatory tools available to responsible authorities in all levels of government for integrating climate change impacts in flood planning and management.

Issue	Investigation
B-2 Flood Hazard Information	1. Investigate the current state of flood mapping in the province, including gaps and limitations. Recommend an approach to improve the spatial coverage, quality, utility and accessibility of flood hazard maps and other flood hazard information.
	2. Investigate the approximate level of effort to prepare flood hazard mapping to address current gaps for existing communities and future areas of development (including floodplain maps and channel migration assessments).
	3. Investigate the current state of knowledge related to dike deficiencies and recommend an approach to improve the quality, consistency, review, utility and accessibility of this information.
	4. Investigate the status of LiDAR standards for flood mapping and develop recommendations to improve standards if applicable.
B-3 Flood Risk Assessment	1. Investigate approaches to completing a province-wide flood risk assessment, addressing effort required, level of detail, types of flood risk, current and future scenarios, scale, and any information required and data gaps.
	2. Determine the effort required to undertake a local-scale comprehensive flood risk assessment for multiple types of flood hazards (e.g. riverine, coastal).and for varying degrees of available data on flood hazard, exposure, vulnerability and risk.
	3. Investigate the effort required to develop and maintain a province-wide asset inventory and/or exposure dataset covering flood prone areas.
	4. Investigate the level of effort to develop a coarse local-scale flood risk map based on available flood hazard map(s).
	5. Investigate methods for valuing the benefits and costs/limitations of flood risk reduction actions in a holistic and consistent manner and develop a framework for project prioritization that could be applied or adapted across the province to reduce flood risk.
	6. Evaluate and compare the benefits and costs/limitations of taking a risk-based approach to flood management versus a standards-based approach.
B-4 Flood Planning	1. Investigate the ability of responsible authorities in the province to develop adaptation plans and strategies for flood management.
	2. Investigate opportunities to improve the knowledge and capacity of local authorities with regard to climate change adaptation and the benefits of proactive flood risk reduction.
	3. Investigate the potential content of a provincial guideline to support the development of local Integrated Flood Management Plans.
	4. Investigate the level of effort for a local authority to complete an Integrated Flood Management Plan and the possible role of the province in reviewing and/or approving these plans.

Issue	Investigation
B-5 Structural Flood Management Approaches	1. Investigate opportunities to incentivize or require diking authorities to maintain flood protection infrastructure and plan for future conditions such as changing flood hazards.
	2. Investigate opportunities to improve the knowledge and capacity of local diking authorities with regard to dike maintenance.
	3. Investigate opportunities to improve coordination amongst diking authorities under non-emergency conditions.
	4. Investigate impediments to and opportunities for implementing innovative structural flood risk reduction measures, including the role of incentives and regulation.
B-6 Non-Structural Flood Management Approaches	1. Investigate past and current approaches to land use and development decisions in floodplains by local and provincial authorities.
	2. Investigate alternatives to the current approach to managing development in floodplains, including returning regulatory authority for development approvals in municipal floodplains to the Province, and provide an analysis of the benefits and costs/limitations of both local and provincial authority.
	3. Investigate impediments to and opportunities for implementing available non-structural flood risk reduction actions, including the role of incentives and regulation.
	4. Investigate the nature of an educational campaign for regional, local and First Nations governments to raise awareness of flood risk and possible risk reduction options.

Theme C. Flood Forecasting, Emergency Response and Recovery

Issue	Investigation
C-1 Flood Forecasting Services	1. Investigate current capacity, coverage, value, and gaps in flood forecasting services.
	2. Visualize where flood forecasting gaps exist and estimate costs for improvement to end users.
C-2 Emergency Response	1. Investigate the future direction of the Federal government related to a National Flood Risk Strategy and the future of Disaster Financial Assistance Arrangements
	2. Investigate the Province’s expanding role in providing flood response to First Nations.
	3. Investigate the status of local authority flood response plans and recommend an approach to manage, update and improve this information.

Issue	Investigation
	4. Investigate flood response capabilities considering different flood hazards and different regions of the province.
	5. Investigate opportunities for improved organizational planning for emergency response in all levels of government.
C-3 Flood Recovery	1. Investigate the current status of coverage of existing overland flood insurance available to home-owners.
	2. Investigate the concept of "build back better" and impediments to implementation.

Theme D. Resources and Funding

Issue	Investigation
D-1 Resources and Funding	1. Investigate resource and funding needs associated with implementing recommendations to strengthen flood management in BC.
	2. Investigate evidence in support of investment in proactive flood planning and mitigation activities.