Appendices

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Disaster and Climate Risk and Resilience Assessment (DCRRA)

Hazard Exposure Analysis

Prepared by BGC Engineering Inc. for:

SAGE ON EARTH CONSULTING

March 24, 2025

Project 1362002

Pioneering responsible solutions to complex earth science challenges

EXECUTIVE SUMMARY

The British Columbia Ministry of Emergency Management and Climate Readiness (BC EMCR) retained Sage On Earth Consulting Ltd. (Sage) to conduct a provincial and regional disaster and climate risk and resilience assessment (DCRRA) for the Province of BC. This report pertains to the provincial phase of the DCRRA, which will inform subsequent regional studies.

As part of Sage's team[1], BGC Engineering Inc. (BGC) completed geospatial analysis to identify the presence and characteristics of valued assets in areas potentially subject to six hazard types selected by EMCR for the Provincial phase: coastal and riverine floods, earthquakes, wildfires, extreme heat, drought and cascading hazards. Cascading hazards (e.g., multiple hazard types occurring through a chain of events) are not explicitly assessed, but results will inform qualitative assessment of cascading hazards by Sage's team. Hazard exposure analysis is a foundational step in the completion of the DCRRA and risk reduction planning. This technical report summarizes BGC's analysis workflow, presents results and deliverables, and describes limitations. It is intended as supporting documentation of the analysis process and should be read with the DCRRA summary report prepared by Sage.

BGC developed a workflow to compile hazard and valued asset geospatial data across BC and determine spatial relationships between these data. BGC engaged with DCRRA Hazard and Value Working Groups for input into analyses inputs, assumptions and workflows. BGC also engaged with GeoBC, the Province of BC's geospatial information management and service centre tasked with developing the "ClimateReadyBC" data portal to disseminate results.

"Hazard exposure" is the term adopted by the broader project team to describe assets located in hazard areas above a defined threshold level of intensity at an annual probability of occurrence, both of which are distinct for each hazard type. For example, flood hazard maps show areas with potential riverine flood inundation for a 1 in 200-year flood (0.5% annual exceedance probability). For provincial scale analysis, valued assets that intersect hazard extents are considered exposed. The entire province is divided into a 0.375 min latitude x 0.75 min longitude (~1.5 km x 1.5 km) grid to report hazard exposure statistics such as the number of people, value of building improvements, and lengths of transportation and utilities assets at exposure within a given grid cell. The results can be totalled province-wide and display patterns of varying hazard exposure across the province.

BGC provides deliverables in the following appendices:

- **Hazard Exposure Analysis Workflows** (Appendix A): summary of hazard exposure analysis methods specific to hazard type.
- **Gaps and Limitations** (Appendix B): summary of analysis gaps and limitations for consideration in subsequent project phases (e.g., regional scale).
- **Data Schema and Hazard Exposure Statistics** (Appendix C): hazard exposure totals for each asset in the schema, by hazard type.

[1] Sage on Earth Consulting (Sage), subcontractors retained by Sage for the DCRRA, and working groups established by Sage to contribute elements of the DCRRA scope of work.

- **Metadata** (Appendix D): information about the format and source of data compiled for analysis.
- **Maps and Charts** (Appendix E): formatted for inclusion in DCRRA reports prepared by the Sage Team. Maps display hazards and hazard exposure for each asset type. Charts provide a visual indicator of hazard exposure for each asset type, for each hazard.
- **Software Code** (Appendix F): for hazard exposure analysis provided as separate files.
- **Geospatial Data** (Appendix G): input data and geospatial processing results in vector grid format for the purpose of displaying results on a data portal. Each 1.5 km x 1.5 km grid includes hazard exposure attributes according to the values shown in Appendix C.

Gaps, uncertainties, and simplifying assumptions exist within all input data, analysis workflows, and outputs generated by this assessment, including but not limited to those described in the main report and Appendix A. For assets, potential gaps in information may lead to underestimation of hazard exposure (e.g., for unidentified hazards), or overestimation (e.g., where areas without hazard are captured due to coarse mapping resolution). For hazards, limitations to hazard data exist at each step of preparing data layers including inputs, workflows, and outputs. For all hazards, is it important to cite the definition of hazard (probability of exceedance and hazard threshold) when describing a valued asset as “exposed”, as hazard extents are based on these criteria. Comparison between hazard types should recognize the range of probabilities associated with different hazard types (e.g., a 1:50-year heat event compared to a 1:2475-year earthquake). With qualified professional input, the analysis process has been designed to efficiently incorporate new data, additional hazards or threshold criteria as may be needed in future to resolve data gaps and incorporate additional use-cases.

TABLE OF REVISIONS

Date	Revision	Remarks
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[2] References in these Limitations to the "document" include the document to which these Limitations are attached, any content contained in this document, and any content referenced in this document (e.g., geospatial data, maps, charts, or software provided).

[3] BGC's scope of work is being completed according to an August 29, 2023, contract and work plan between SOE and BGC (with change-order request No. 1 (09/29/2023), No. 2 (12/22/2023), No. 3 (05/01/2024), and No. 4 (05/21/2024).

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1.0 INTRODUCTION

1.1 General

The British Columbia Ministry of Emergency Management and Climate Readiness (BC EMCR) retained Sage On Earth Consulting Ltd. (Sage) to conduct a Disaster and Climate Risk and Resilience Assessment (DCRRA) for the Province of BC. Sage retained BGC Engineering Inc. (BGC) as technical lead for geospatial data compilation and hazard exposure analyses.

BGC's objective is to complete geospatial analysis to identify the presence and characteristics of valued assets in areas potentially subject to six hazard types selected by EMCR for the Provincial Phase: coastal and riverine floods, earthquakes, wildfires, extreme heat, drought and cascading hazards (Figure 1-1). The process is termed 'hazard exposure analysis', and valued assets intersecting hazard extents are considered 'exposed'. Cascading hazards (e.g., multiple hazard types occurring through a chain of events) are not explicitly assessed, but BGC's results for single hazard types will inform qualitative assessment of cascading hazards by the DCRRA team. The results of the hazard exposure analysis will inform disaster risk assessment, management, and communication planning by the Provincial government, First Nations, and additional parties through the sharing of assessment results.

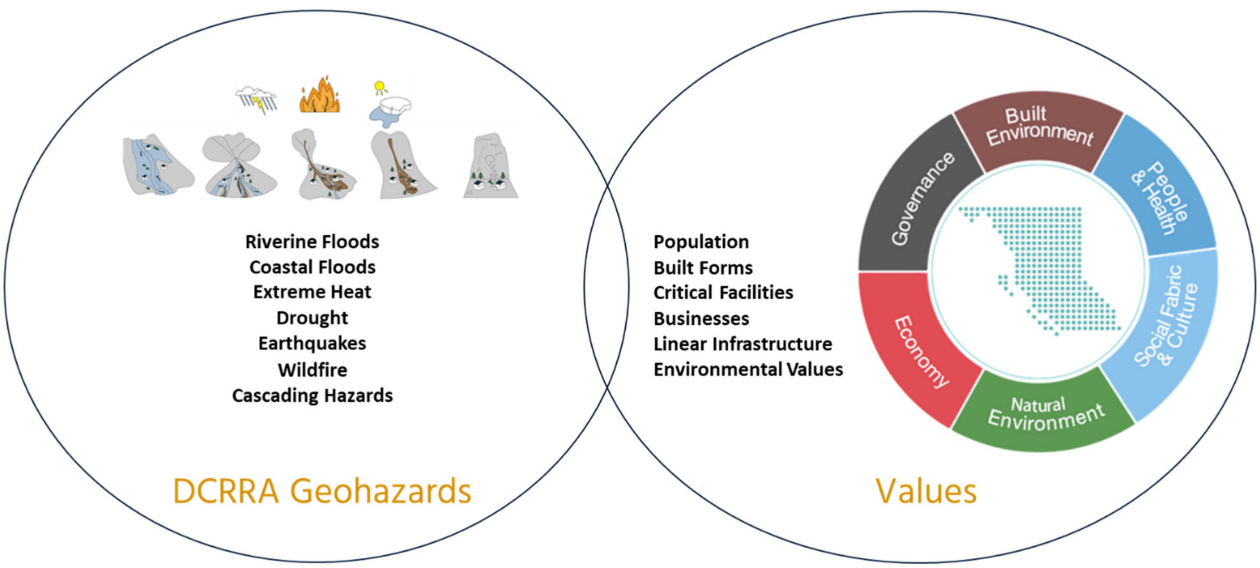

Figure 1-1 Conceptual illustration of the hazard exposure analysis objective: to identify the presence and characteristics of valued assets in areas potentially subject to the hazard types included in the DCRRA (as suggested by intersection of the two ovals).

This hazard exposure analysis is based on existing, externally sourced asset data. Hazard layers for drought, co-seismic landslide potential, co-seismic liquefaction potential, and coastal flood were prepared by BGC as part of the project scope. BGC developed the riverine flood hazard layer as separate project with BC Hydro, shared with the Province of BC. Pacific Climate Impacts Consortium (PCIC) prepared the heat layers. The wildfire hazard layer was sourced from the BC Wildfire Service. See Section 3.0 and Appendix D for data sources.

Hazard exposure analysis is a foundational step in the completion of disaster risk assessment to identify areas with a threshold level of hazard exposure, inform risk reduction planning at a provincial level, and complete subsequent steps of work at a regional-local level. BGC's analysis results are provided to GeoBC for publication on the provincial "ClimateReadyBC" data portal being developed by GeoBC for the Province, and to the Sage Team for qualitative disaster risk assessment completed by project team working groups.

This report summarizes BGC's project deliverables and the analysis workflow. It is intended as technical documentation that should be read with the DCRRA project report prepared by the Sage Team, and hazard exposure analysis results displayed via the ClimateReadyBC data portal. The main part of this document summarizes components of the analysis common to all hazards considered. Appendices describe steps of analysis specific to different hazard types, and list the deliverables provided separately (spreadsheets, data and software code).

1.2 Scope of Work

The DCRRA project extends from 2023-2026, including a first phase of province-wide hazard exposure analysis followed by regional scale assessments. This report pertains to the first (provincial) phase of the DCRRA.

Table 1-1 summarizes BGC's scope of work, including geospatial analysis; engagement with the Sage Team, EMCR and GeoBC; and preparation of deliverables.

Table 1-1 Scope of work.

Work Phase	Description	Activities
1	**Project Management**	
1.1	Project Management	Project administration
2	**Geospatial Analysis**	
2.1	Multi-Asset Data Model	Compilation and assembly of asset data in the format required for hazard exposure analysis.
2.2	Multi-Hazard Data Model	Compilation and assembly of hazard data in the format required for hazard exposure analysis.
2.3	Geospatial Analysis	Geospatial analysis of hazard exposure, including software development for spatial analysis workflows.
2.4	Hazard Layer Development (Drought)	Development of hazard layers for hazard exposure analysis of drought
2.5	Hazard Layer Development (Coastal Flood)	Development of hazard layers for hazard exposure analysis of coastal floods
3	**Project Engagement**	
3.1	Working Group Participation	BGC participation in “Hazard” and “Value” working groups undertaking separate scopes of work for the Sage project team.
3.2	Geospatial Analysis Engagement:	BGC engagement with GeoBC, EMCR, and the Sage Team to develop, communicate and confirm geospatial analysis inputs, processes, and outputs.
4	**Deliverables**	
4.1	Process Reporting; Data Documentation	Preparation of project documents
4.2	Geomatics/Geospatial Data Delivery and Metadata	Delivery of geospatial data resulting from geospatial
4.3	DCRRA Main Report Input	Providing map and chart outputs for DCRRA Main Report

1.3 Level of Detail

Table 1-2 provides three-tiered criteria for level of detail of assessment, simplified from draft Provincial Floodplain Mapping Guidelines under development for BC Ministry of Water, Lands, and Resource Stewardship (WLRS). This provincial scale hazard exposure analysis has been completed at a Tier 1 level of detail. Both the data structure and analysis methods have been designed to accommodate further refinement to higher levels of detail in future. BGC provides additional limitations of use in Section 4.0 and Appendix B.

Table 1-2 Tiers 1 through 3 hazard mapping. Adapted and generalized from Draft flood hazard mapping standards (in-progress for WLRS).

Level	Description
Tier 1	Hazard identification (screening-level) - hazard identification maps help identify areas susceptible to a particular hazard across large spatial scales using desktop approaches.
Tier 2	Base-level hazard mapping - hazard maps further refine the Tier 1 results to better characterize hazards over larger areas and are a precursor to more costly detailed mapping using modelling approaches.
Tier 3	Detailed-level hazard mapping - further refines estimates of hazard extents and characteristics across a range of scenarios at greater detail than base level maps by including high resolution data (e.g., site-scale survey data). Can include considerations for climate change. Detailed hazard maps may include multiple hazard scenarios, delineation of construction setback guidelines, and can be used to inform policy, risk assessment, and risk management decisions.

2.0 ANALYSIS WORKFLOW

BGC developed a workflow to compile hazard and valued asset geospatial data and determine spatial relationships between these data. The process is termed “hazard exposure analysis”, and assets that spatially intersect hazard extents are considered exposed (e.g., are assumed to have credible potential for loss, at the scale of province-wide assessment). The process was developed by BGC staff using geospatial and analysis libraries available in Python (Appendix F) and is consistent across hazard types.

The software code and associated documentation provides the most detailed description of geospatial analysis methods. Appendix A summarizes analysis workflow in general and provides hazard-specific requirements or processing steps that were included as part of the hazard exposure analysis.

BGC engaged with the following DCRRA working groups to select the chosen data inputs and to discuss analysis workflows specific to each hazard type:

- Hazard Working Group Meetings:
  - Seismic – February 15, 2024
  - Flooding - February 29, 2024
  - Extreme Heat – March 1, 2024
  - Drought – March 11, 2024
  - Wildfire – March 15 and 19, 2024
- Value Groups
  - Built Environment – March 7, 2024
  - Natural Environment – February 29, 2024
  - Economy – March 1, 2024
  - Health and Wellbeing – March 15, 2024.

BGC presentations are on file with Sage, and the hazard and asset data models carried through spatial analysis considered, and, where possible, integrated the feedback provided by each working group. The data inputs chosen reflected working group input, a requirement for continuous, study area - wide coverage at consistent level of detail, and format (e.g. as required for hazard exposure analysis, as described in Appendix A). BGC notes that the workflows are designed to be run on higher resolution datasets during subsequent phases of assessment, where available.

Figure 2-1 provides a generalized illustration of the hazard exposure modelling process for assets of different geometry types (i.e., point, polyline, or polygon). In summary, the process determines where areas of hazard exposure exist. It then quantifies the exposure based on a total area (e.g., total area of parks exposed to a given hazard) or area weighted sum (e.g., proportional population relative to area exposed to a given area), length (for linear asset data), and count (for point-based asset data).

Data processing outputs were generalized to a 0.375 min latitude x 0.75 min longitude (~1.5 km x 1.5 km) grid covering the entire province[4]. Hazard exposure statistics are summarized using the grid (e.g., to determine the count or value of assets exposed within a given grid).

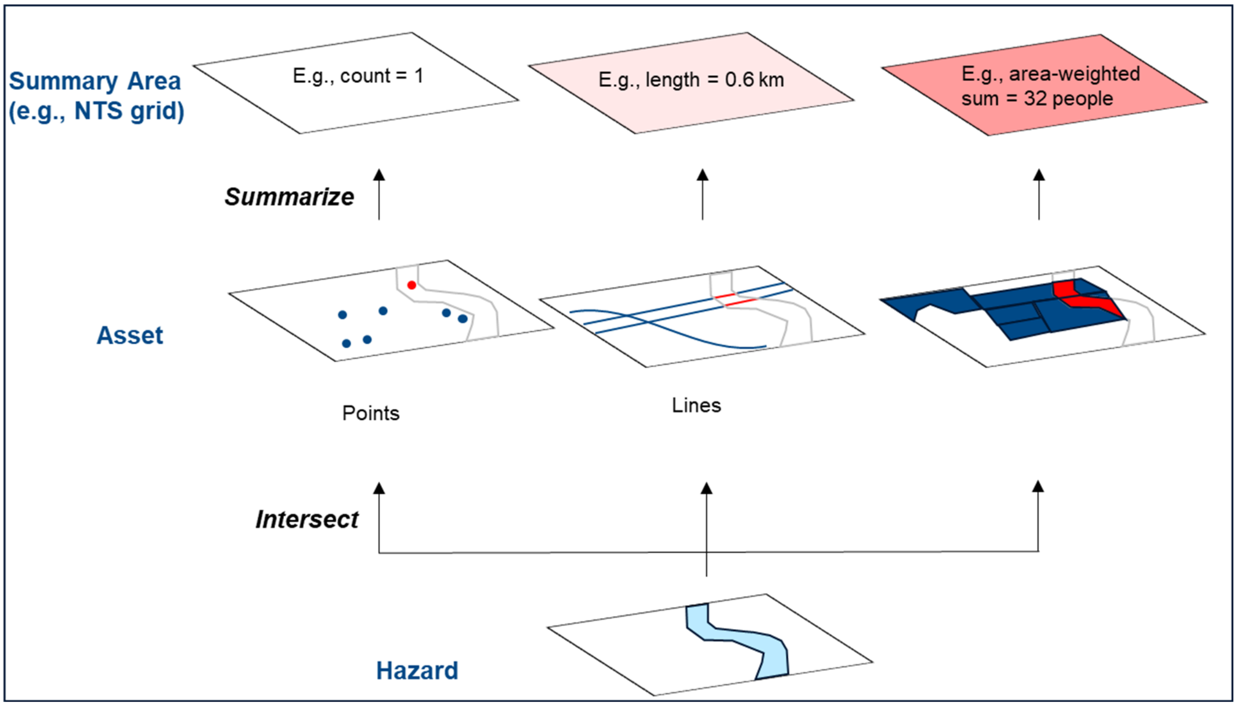

Figure 2-1 Conceptual diagram outlining the hazard exposure analysis workflow.

[4] 1:2,500 scale NTS grid, 0.375 min latitude x 0.75 min longitude. Actual dimensions vary with latitude but have approximate dimensions of 1.5 km by 1.5 km.

3.0 DELIVERABLES

BGC provides deliverables in the following appendices:

- **Hazard Exposure Analysis Workflows** (Appendix A): summary of hazard exposure analysis methods specific to hazard type.
- **Gaps and Limitations** (Appendix B): summary of analysis gaps and limitations for consideration in subsequent project phases (regional scale).
- **Data Schema and Hazard Exposure Statistics** (Appendix C): hazard exposure totals for each asset in the schema, by hazard type.
- **Metadata** (Appendix D): information about the format and source of data compiled for analysis.
- **Maps and Charts** (Appendix E): formatted for inclusion in DCRRA reports prepared by the Sage Team. Maps display hazards and hazard exposure for each asset type. Charts provide a visual indicator of hazard exposure for each asset type, for each hazard.
- **Software Code** (Appendix F): for hazard exposure analysis provided as separate files.
- **Geospatial Data** (Appendix G): input data and geospatial processing results in vector grid format for the purpose of results display on a data portal. Each 1.5 km x 1.5 km grid includes hazard exposure attributes according to the values shown in Appendix C.

Asset and hazard data compiled for hazard exposure analysis reflect a need for province-wide coverage in a consistent geospatial format. This section summarizes hazard and asset data inputs and hazard exposure analysis outputs, with reference to Appendices A-E, which provide further details specific to hazard types.

3.1 Assets

BGC assembled a province-wide asset data model that includes population and population groups totalling about 4.8M people, built form[5] totalling about $860B in assessed value, critical facilities, businesses, about 720,000 km of roads, over 10,000 km of railways, and over 250,000 km of linear utilities.

Appendix C and Table 3-1 provide a schema listing valued assets in the format used to deliver hazard exposure analysis results. Appendix D lists asset data sources and associated metadata. Appendix A provides a further breakdown of the built form included in the critical facility categories shown in Table 3-1. Appendix B summarizes gaps and limitations of the asset data model, which should not be considered exhaustive.

The spatial format of the asset data (points, lines, or polygons) and their attributes determine how hazard exposure is indicated. An exposed asset partially or wholly intersects a given hazard extent. The description field in Table 3-1 indicates the measure used to indicate

[5] Improvements on land parcels are referred to as built form in this document. The term ‘built form’ refers to any building, fixture, structure or similar thing constructed or placed on or in land, or water over land, or on or in another improvement but does not include any of the following unless that thing is a building: (a) product machinery,; (b) anything intended to be moved as a complete unit in its day to day use; (c) furniture or equipment that is not affixed for any purpose other than its own stability and that is easily moved by hand (Assessment Act, 1996). From BC Assessment Glossary. The built form categories shown in Figure 3-3 are the same as BCA Actual Use groups.

exposure for a specific asset (count, area, dollar value, or length). Hazard exposure identifies potential for loss but does not indicate a level of hazard or vulnerability for a given asset. Further limitations are outlined in Appendix B.

Table 3-1 Asset data schema.

Asset Group	Name[6]	Description	Unit	Source
Population (2021)	Population Total	Population Total	count (integer)	NRCan Physical and Social Fabrics (with update by GeoBC to reflect 2021 Census data)
Population (2016)	Population Total	Population Total	count (integer)	NRCan Physical and Social Fabrics
	Population Living Alone	Population Living Alone	count (integer)	
	Population that Moved within Last Year	Population that Moved within Last Year	count (integer)	
	Population Immigrated within Last 5 Years	Population Immigrated within Last 5 Years	count (integer)	
	Population with No Knowledge of English/French	Population with No Knowledge of English/French	count (integer)	
	Population with No Secondary School Education	Population with No Secondary School Education	count (integer)	
	Population Older than 65 Years	Population Older than 65 Years	count (integer)	
	Population Younger than 6 Years	Population Younger than 6 Years	count (integer)	
	Population with Indigenous Heritage	Population with Indigenous Heritage	count (integer)	
	Population that are a Visible Minority	Population that are a Visible Minority	count (integer)	
	Labour Force Population that is Unemployed	Labour Force Population that is Unemployed	count (integer)	
	Population that Receives Employment Income	Population that Receives Employment Income	count (integer)	

[6] Attribute field names are indicated in Appendix D (Metadata).

Asset Group	Name[6]	Description	Unit	Source
Households (2016)	Households with Only 1 Maintainer	Households with Only 1 Maintainer	count (integer)	NRCan Physical and Social Fabrics
	Lone Parent Families with 3 Children	Lone Parent Families with 3 Children	count (integer)	
	Families with more than 5 Members	Families with more than 5 Members	count (integer)	
	Households where Shelter Costs Exceed 30% of Income	Households where Shelter Costs Exceed 30% of Income	count (integer)	
	Households in Lower Income Decile	Households in Lower Income Decile	count (integer)	
Population Within a Social Vulnerability Range	[0-4]	Population with Average Social Vulnerability Index between 1-4	count (integer)	NRCan Social Fabric
	(4-8]	Population with Average Social Vulnerability Index between 4-8	count (integer)	
	(8-12]	Population with Average Social Vulnerability Index between 8-12	count (integer)	
	>12	Population with Average Social Vulnerability Index >12	count (integer)	
Built Form (Replacement Value, First Nations Reserves)	All	Built Form – All	dollars (integer)	NRCan (2016)
Built Form (Improvements – e.g. buildings)	Type	All	dollars (integer)	Province of BC
		Residential	dollars (integer)	
		Farm	dollars (integer)	
		Commercial	dollars (integer)	
		Industrial	dollars (integer)	
		Transportation, Communication and Utility	dollars (integer)	
		Stratified Operational Facility Areas	dollars (integer)	
		Civic, Institutional and Recreational	dollars (integer)	

Asset Group	Name[6]	Description	Unit	Source
Critical Facilities[7]	Type	Critical Facilities (all)	count (integer)	BC Assessment
		Emergency Response Services: Emergency Operations Center, Government Buildings (Offices, Fire Stations, Ambulance Stations, Police Stations).	count (integer)	
		Emergency Response Resources: Asphalt Plants, Concrete Mixing, Oil & Gas Pumping & Compressor Station, Oil & Gas Transportation Pipelines, Petroleum Bulk Plants, Works Yards.	count (integer)	
		Utility: Electrical Power Systems, Gas Distribution Systems, Water Distribution Systems, Hydrocarbon Storage.	count (integer)	
		Communication: Telecommunications.	count (integer)	
		Food	count (integer)	
		Medical: Hospitals, Group Home, Seniors Independent & Assisted Living, Seniors Licenses Care.	count (integer)	
		Transportation: Airports, Heliports, Marine & Navigational Facilities, Marine Facilities (Marina), Service Station.	count (integer)	
		Environmental: Garbage Dumps, Sanitary Fills, Sewer Lagoons, Liquid Gas Storage Plants, Pulp & Paper Mills.	count (integer)	
		Community: Government Buildings, Hall (Community, Lodge, Club, Etc.), Recreational & Cultural Buildings, Schools & Universities, College or Technical Schools.	count (integer)	
Businesses	Number and Value measures	Total Annual Revenue (approximate)	dollars (integer)	Geografx
		Businesses	count (integer)	
Environmental Values	Type	Old Growth Management Areas	area (km^2)	GeoBC
		Parks and Protected Areas	area (km^2)	GeoBC
		Fisheries Information Summary System (FISS) locations	count (integer)	GeoBC
		Species and Ecosystems at Risk	area (km^2)	BC Conservation Data Center

[7] Facilities that are important in terms of their continued function during an emergency.

Asset Group	Name[6]	Description	Unit	Source
Roads	Classification	Road or Highway Alignment (Unclassified)	length (km)	BC Digital Road atlas; MoTI Road Network
		Road or Highway Alignment (Class 1, > 10,000 Vehicles/Day)	length (km)	
		Road or Highway Alignment (Class 2, 5,000-10,000 Vehicles/Day)	length (km)	
		Road or Highway Alignment (Class 3, 1,000-5,000 Vehicles/Day)	length (km)	
		Road or Highway Alignment (Class 4, 500-1,000 Vehicles/Day)	length (km)	
		Road or Highway Alignment (Class 5, 100-500 Vehicles/day)	length (km)	
		Road or Highway Alignment (Class 6, 10-100 Vehicles/day)	length (km)	
		Road or Highway Alignment (Class 7, 0-10 Vehicles/day)	length (km)	
		Road Alignment (Class 8, No Summer Maintenance)	length (km)	
Railway		Railway Alignment	length (km)	National Railway Network
Utilities (Linear Infrastructure)	Type	Petroleum Pipeline Alignment	length (km)	ICI Society (primary); Municipal data (incomplete)
		Electrical Infrastructure Alignment	length (km)	
		Water Infrastructure Alignment (Centerlines)	length (km)	
		Communication Infrastructure Alignment	length (km)	
Utilities (Point Infrastructure)	Type	Electrical Infrastructure Locations (Poles and Towers)	count (integer)	
		Communication Infrastructure Locations (Poles and Towers)	count (integer)	
		Petroleum Pipeline Locations (location of built form related to pipelines assets)	count (integer)	

3.2 Hazard Layers

Table 3-2 defines each hazard in terms relevant to hazard exposure analysis and cites data sources further described in Appendix D (Metadata). In summary:

- Meterological drought, seismic (ground shaking, co-seismic landslide potential, co-seismic liquefaction potential), and coastal flood hazard layers were developed by BGC as part of this project, based on the analysis of data from sources cited in Table 3-2. Appendix A provides additional details on the development of these layers.
- The riverine flood hazard layer was developed by BGC (April 19, 2014) for BC Hydro, with results shared for the DCRRA. For completeness, Appendix A summarizes layer development methods reported by BGC (April 19, 2024).
- Heat and wildfire hazard layers were provided by PCIC (2024) and BC Wildfire Service (BCWS, 2019). Documentation provided in Appendix A is limited to describing how these existing layers were incorporated into hazard exposure analysis.

For hazard exposure analysis, “hazard” is defined as the areal extent above a threshold level of hazard intensity, at an annual probability of exceedance. This definition of hazard is consistent across hazard types, but annual probability and intensity thresholds differ between hazard types.

For example, flood hazard maps show areas with potential riverine flood inundation for a 1 in 200-year flood (0.5% annual exceedance probability, AEP). In this example, “probability” corresponds to 1 in 200-year flood and “intensity threshold” is anywhere with greater than zero modelled flood depth.

As a second example, the baseline heat hazard map shows areas where the 50-year return period for 3-day average daily mean (1971-2000) temperature exceeds the average Environment and Climate Change Canada's heat warning for a given ECCC heat warning region. In this example, “probability” corresponds to a 1:50 year heat event, and “intensity threshold” is anywhere that the temperature exceeds the ECCC heat warning criteria.

This definition provides a binary (yes/no) way to address the question, ‘is the asset exposed to hazard?’, providing statistics about hazard exposure that can be consistently summarized province-wide or depicted for areas of interest.

The hazard thresholds were selected based on advice and input from the hazard working group members or technical advisors. They reflect requirements to analyse a large and diverse asset data model for six different hazard types at Province-wide scale. Section 4.0 notes limitations and opportunities to further explore hazard exposure via additional hazard probabilities and threshold criteria, refine analysis to greater detail, or incorporate additional risk parameters (e.g., vulnerability). Appendix B further describes gaps and limitations related to hazard inputs.

Table 3-2 Hazard definitions.

<table>
<tr><th>Category</th><th>General Definition</th><th>Hazard Processes</th><th>Definition</th><th>Threshold Value</th><th>Source</th></tr>
<tr><td rowspan="6">Seismic</td><td rowspan="6">Earthquake events</td><td rowspan="4">Ground shaking</td><td rowspan="4">Areas exceeding peak ground acceleration (PGA) hazard thresholds (>0.09 g, >0.28 g) or exceeding peak ground velocity (PGV) thresholds (>125 mm, >250 mm) for a 1 in 2475-year earthquake shaking scenario</td><td>PGA > 0.09 g</td><td rowspan="6">Kolaj et al. (2023); Cui, Y., Miller, D., Schiarizza, P., & Diakow, L.J. (2017); Geological Survey of Canada (GSC). (2014)</td></tr>
<tr><td>PGA > 0.28 g</td></tr>
<tr><td>PGV > 250 mm/s</td></tr>
<tr><td>PGV > 125 mm/s</td></tr>
<tr><td>Co-seismic landslides</td><td>Areas with potential co-seismic landslide hazards for the 1 in 2475-year earthquake shaking scenario</td><td>PGA exceeds critical acceleration value</td></tr>
<tr><td>liquefaction</td><td>Areas exceeding liquefaction hazard threshold (potentially liquefiable soils with a PGA>0.09g) for the 1 in 2475-year earthquake shaking scenario</td><td>PGA > 0.09 g and surficial material type is susceptible to liquefaction</td></tr>
<tr><td rowspan="3">Flooding</td><td rowspan="3">Flooding of rivers or sea level rise</td><td>Clear water floods</td><td>Areas with potential riverine flood inundation for a 1 in 200-year flood using the Tier 1 floodplain layer</td><td>Hazard extent</td><td>BGC Engineering Inc. (April 19, 2024)</td></tr>
<tr><td>Coastal inundation - Baseline</td><td>Coastal flood elevation including sea level rise (2020) + mean higher high water (mhhw) + Storm Surge (Hindcast, 99th Percentile, 2000 to 2020)</td><td>Hazard extent</td><td rowspan="2">This report, based on analysis of data provided by National Research Council Canada (NRC) per Cousineau and Murphy (2022)</td></tr>
<tr><td>Coastal inundation - climate change</td><td>Coastal flood elevation including sea level rise (2100) + mean higher high water + Storm Surge (Multi-model Maximum, 2080 to 2099)</td><td>Hazard extent</td></tr>
<tr><td>Wildfire</td><td>Uncontrolled burning of wildland vegetation.</td><td>Wildfire</td><td>Areas where the 2019 Provincial Strategic Threat Analysis (PSTA) Wildfire Threat Rating at least 6 (Moderate)</td><td>Wildfire Threat Level at least 6</td><td>BC Wildfire Service (2019)</td></tr>
</table>

Category	General Definition	Hazard Processes	Definition	Threshold Value	Source
Climate	Hazards related to weather events	Extreme heat (baseline)	Areas where the 50-year return period for 3-day average daily mean (1971-2000) exceeds the average Environment and Climate Change Canada's heat warning threshold (average of daytime maximum and overnight minimum temperature) for a given ECCC heat warning region.	N BC- Tmax >29 oC and Tmin >14 oC; S BC - Tmax >35 oC and Tmin >18 oC; SW BC- Tmax >29 oC and Tmin >16 oC; NW BC - Tmax >28 oC and Tmin >13 oC; Cascades - Tmax >33 oC and Tmin >17 oC	Pacific Climate Impacts Consortium (PCIC) (March 12, 2024)
		Extreme heat (climate change)	Areas where the 50-year return period for 3-day average daily mean (2041-2070, three emission scenarios: SSP2-4.5, SSP3-7.0, SSP5-8.5) exceeds the average Environment and Climate Change Canada's heat warning threshold (average of daytime maximum and overnight minimum temperature) for a given ECCC heat warning region (5 regions across BC).		
		Meterological drought (baseline)	Areas where the 50-year return period 12-month Standardized Precipitation Evapotranspiration Index (SPEI) value (1950-2014, median of 25 global climate models assuming SSP5-8.5) exceeds the threshold for extreme drought (SPEI < -2)[8]	SPEI < -2	This report, based on analysis of data provided by ECCC (Tam et al., 2023)
		Meterological drought (climate change)	Areas where the 50-year return period 12-month Standardized Precipitation Evapotranspiration Index (SPEI) value (2041-2070, median of 25 global climate models assuming SSP5-8.5) exceeds the threshold for extreme drought (SPEI < -2)	SPEI < -2	

[8] For clarity on why GCM outputs are relevant to both the baseline and climate change-adjusted drought layers: the GCM outputs are bias corrected to gridded observational data and downscaled using multivariate techniques. That means that while they are GCM outputs, the results over the baseline period align with observational data. Using GCM outputs allows an apples-to-apples comparison of GCM data for the past and future. As a standardized, relative index, the baseline meteorologic drought layer was developed as a check on methodology. Only the climate change layer was carried through spatial analysis.

3.3 Hazard Exposure Analysis

Figure 3-1 and Figure 3-2 show example maps of riverine flood hazard and flood hazard exposure to built form[9] across BC, where "higher" means a higher assessed value of built form in flood hazard extents. Figure 3-3 provides an example chart of flood hazard exposure for built form. Appendix C (Data Schema) lists province-wide totals for all hazard exposure statistics analysed, and the geospatial data (Appendix G) provides results at an individual grid level of detail.

Table 3-2 clarifies the precision of hazard exposure statistics reported in province-wide totals (Appendix C). Hazard exposure analysis results provided in geospatial data (Appendix G) have not been rounded. Given uncertainties in the analysis of such a large dataset, provincial totals reported on the data portal under development by GeoBC should not be reported at a greater level of precision than shown in Table 3-2.

[9] The term 'built form' refers to "improvements" inventoried by BC Assessment, and includes any building, fixture, structure or similar thing constructed or placed on or in land, or water over land, or on or in another improvement but does not include any of the following unless that thing is a building: (a) product machinery,; (b) anything intended to be moved as a complete unit in its day to day use; (c) furniture or equipment that is not affixed for any purpose other than its own stability and that is easily moved by hand. Source: Assessment Act 1996. From BC Assessment Glossary. The built form categories shown in Figure 3-3 are the same as BCA Actual Use groups. On First Nations Reserves without BC Assessment data, BGC relied on estimated building replacement values of Natural Resources Canada (2022a,b).

Figure 3-1 Riverine flood hazard where floodplains are based on modelled 1:200-year flood extents for a minimum catchment area of 10 km² (example map of hazard extent).

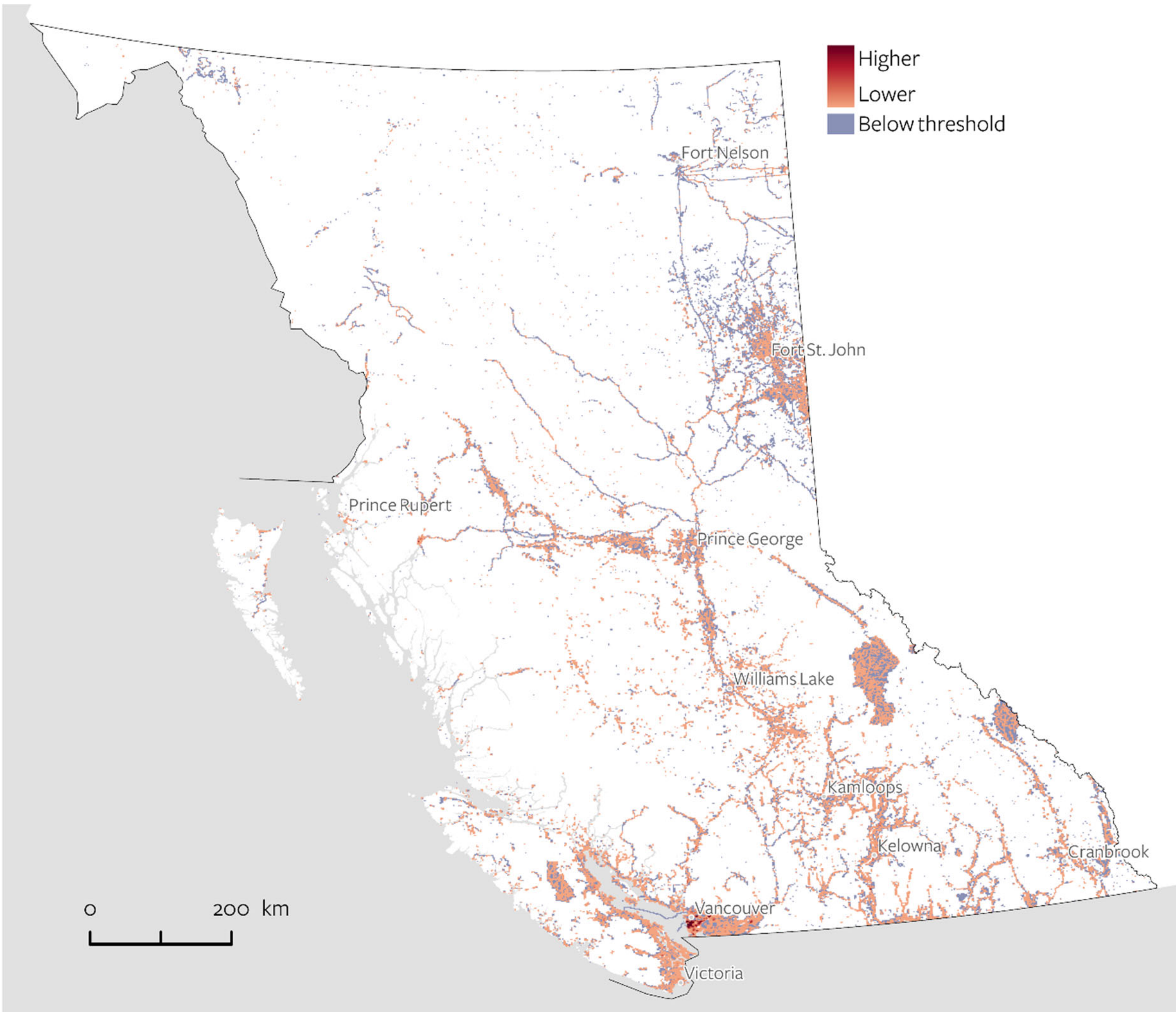

Figure 3-2 Built Form improvement values potentially exposed to riverine floods, based on the flood hazard extents shown in Figure 3-1 (example map of hazard exposure).

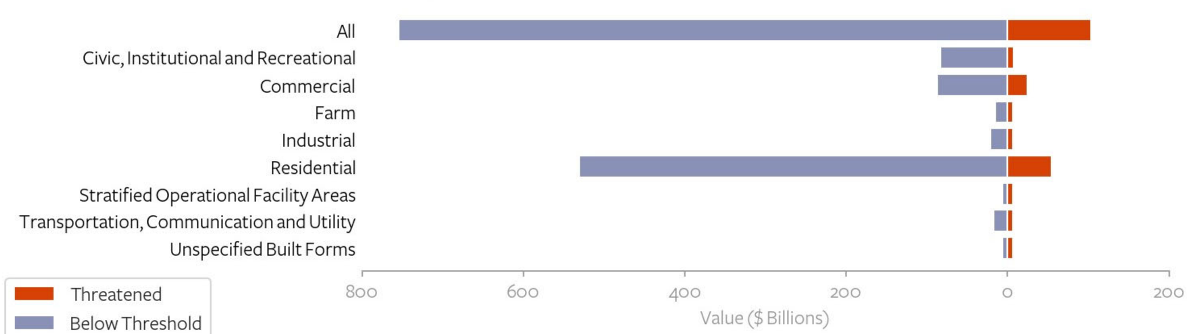

Figure 3-3 Types of Built Form improvements potentially exposed to riverine floods, based on the flood hazard extents shown in Figure 3-1 (example plot of hazard exposure).

Table 3-3 Rounding of Province-wide hazard exposure assessed value totals reported in Appendix C.

Value	Rounded to Nearest
100B+	10B
10B	1B
1B	100M
100M	10M
10M	1M
1M	100k
100k	10k
10k	1k

4.0 DISCUSSION AND LIMITATIONS

Appendix B lists gaps and limitations of hazard and asset input data, and geospatial analysis. The list is not exhaustive, and BGC has included a summary of implications and considerations to resolve gaps. Appendix B does not include a complete list of assumptions, gaps and limitations that may be associated with externally sourced data, which can be accessed through the links or references listed in (Appendix D).

BGC notes that the hazard exposure analysis is based on a single combination of hazard probability and threshold criteria, for a given hazard. All hazards considered follow a frequency-magnitude relationship, and there are unlimited other hazard probabilities and intensity threshold criteria that could be considered besides those included in this study.

The intention is to provide a representation of hazard exposure that can inform decision making (e.g., disaster risk reduction planning), not to provide a complete list of all possible scenarios that could create exposure. Assets not identified as "exposed" fall outside the criteria used to indicate exposure, based on available data. The possibility of hazard exposure based on other criteria or input data cannot be ruled out. All inputs are a snapshot in time, and changed conditions for either valued assets or hazard conditions may result in hazard exposure not identified in this study.

BGC also emphasizes that the hazard types considered in this analysis do not have the same probability of occurrence (e.g., 1:50-year extreme heat, compared to 1:200-year floods, compared to a 1 in 2475-year earthquake). As such, comparison of hazard exposure results between hazard types should be done with caution.

BGC emphasizes the efficiencies gained by using a common workflow to analyze hazard exposure for hazard and asset data assembled province wide. The results can then be carried into subsequent steps of disaster risk assessment and management specific to parties with different roles and responsibilities. With involvement of Qualified Professionals with domain expertise, the analysis can be adapted in future for other hazard probabilities and threshold criteria, additional hazard types, or different areas of interest. The workflow will enable potential refinement with higher resolution data or additional risk parameters (e.g., vulnerability). Operational workflows used to deliver geospatial results to GeoBC may also inform how future assessments can be brought into a consistently maintained knowledge base.

5.0 CLOSURE

This report contains sections under the supervision of different individuals. Kris Holm is the responsible author for the overall hazard exposure analysis (Main Report). Sophia Zubrycky is the responsible author for BGC's Seismic hazard layer development (Appendix A, Section A-4). Melissa Hairabedian is the responsible author for BGC's Drought hazard layer development (Appendix A, Section A-8). Brett Eaton is the responsible author for BGC's Coastal hazard layer development. Richard Carter is the responsible author for geospatial data analysis workflows (Appendix A, Section A-2).

We trust the above satisfies your requirements. Should you have any questions or comments, please do not hesitate to contact us.

Yours sincerely,

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REFERENCES

References are provided in Appendix A

APPENDIX A
HAZARD EXPOSURE ANALYSIS WORKFLOWS

TABLE OF CONTENTS

A-1 INTRODUCTION

This appendix summarizes the hazard exposure analysis workflows undertaken by BGC Engineering Inc. (BGC) as part of the team led by Sage On Earth Consulting (Sage) in support of the Disaster and Climate Risk and Resilience Assessment (DCRRA) project for the Province of British Columbia (BC).

This workflow was undertaken to develop a provincial scale spatial dataset with data about assets considered exposed to the hazard types assessed in the DCRRA. The deliverable format is intended as input for the preparation of visual materials, including static maps and charts prepared by BGC, and an online data portal being developed by GeoBC. While the workflow is limited to hazard exposure analysis, the work also provides a step towards risk analysis and may increase the efficiency of such work if completed in future.

Section A-2 summarizes the overall hazard exposure analysis workflow, and Section A-3 describes asset data inputs for hazard exposure analysis. Sections A-4 to A-8.1 describe workflows by hazard type, organized under the following sub-chapter headers:

- Hazard definition
- Data inputs used in the analysis, with reference to Appendix D (metadata)
- Hazard layer development (co-seismic, coastal flood, riverine flood, and drought hazards only[1])
- Hazard exposure analysis logic
- Gaps and limitations.

Appendix D (Metadata) cites the data sources used for analysis, which primarily include hazard and asset data sources developed outside of the DCRRA project.

A-2 HAZARD EXPOSURE ANALYSIS WORKFLOW

The hazard exposure analysis workflow follows a consistent logic for each hazard type considered. This process is illustrated in Figure A-2-1. The process includes the following main steps:

- Compile asset and hazard data inputs (Box 1 in Figure A-2-1)
- Intersect hazard with valued assets (Box 2 in Figure A-2-1)
- Summarize and generate hazard exposure results in a spatial format defining the areas of interest (Box 3 in Figure A-2-1).

For provincial scale analysis, BGC has used the 1:2,500 scale NTS grid as the spatial format to compute and summarize hazard exposure within each grid across the entire Province. Grid dimensions are 0.375 min latitude x 0.75 min longitude, which corresponds to about a 1.4 km x 1.8 km grid at 49 degrees northern latitude (southern BC) and 1.4 m x 1.4 km at 60 degrees

[1] BGC describes workflows for hazard maps developed as part of the scope of work, and otherwise refers to original data sources for hazard layer development. While BGC developed the flood hazard layer under separate contract with BC Hydro, the hazard layer development approach is also summarized herein.

northern latitude (northern BC). For simplicity, BGC refers to a 1.5 km x 1.5 km grid in this report.

BGC provides hazard exposure summary statistics for each grid cell. For each grid, the output contains a summary of the asset values (e.g., population counts, monetary value of buildings and businesses, length of linear infrastructure) exposed and not exposed. BGC staff developed this process using Python Programming Language libraries (Appendix F).

Units of the value assigned to an exposed asset are indicated in the Data Schema (Appendix C; e.g. length, monetary value, or quantity). For those working with the geospatial data, BGC notes that a value of “NULL” is assigned to assets not identified as exposed. For clarity, BGC notes that in rare cases the assessed value of a built form asset may be zero (0) (i.e., it is possible to have a value of zero for a built form exposed to hazard; zero is not the same as NULL).

Given the volume of data inputs and the provincial-scale analysis, the hazard exposure analysis process was optimized to limit processing time. As such, all data was spatially partitioned using Regional District jurisdictional boundaries. Each hazard/asset combination was processed separately in parallel. Processing was completed on a PC with an AMD Ryzen 9 7950X processor with 16 cores and 32 logical processors, allowing for 31 processes to be run in parallel at once. Total processing time for all hazards/assets across the entire province was approximately 40 hours.

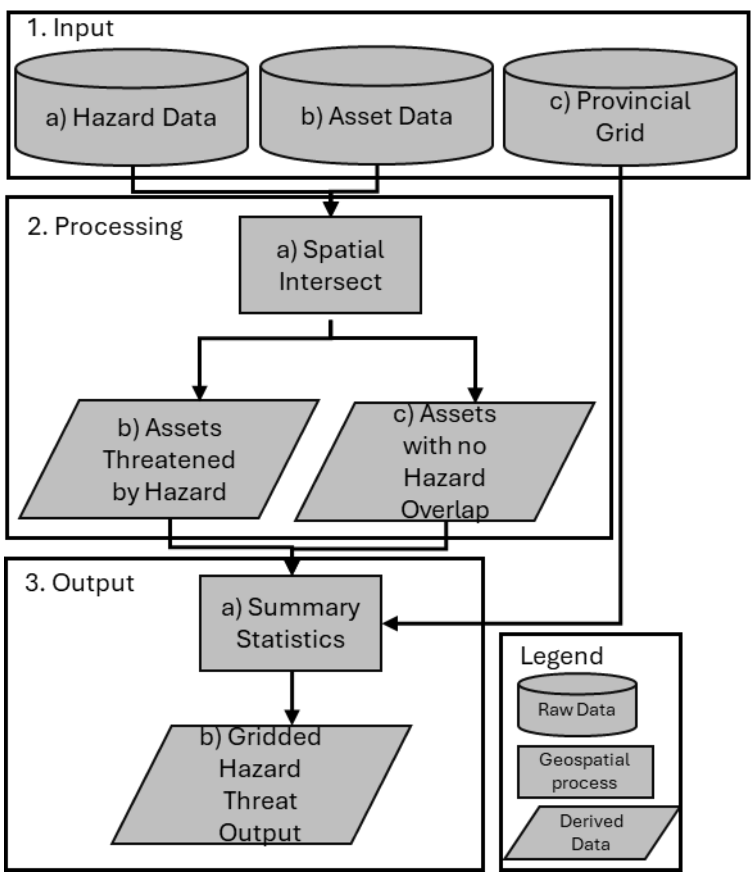


Figure A-2-1 Overview of hazard exposure analysis workflow.

A-3 ASSET DATA INPUTS FOR HAZARD EXPOSURE ANALYSIS

A-3.1 Summary

BGC relied on third-party sources to compile asset data (Appendix D). Data preparation involved organizing these data in groupings and in the required format for hazard exposure analysis. This section summarizes the assets considered for a given hazard type. BGC also provides additional information for select assets where data preparation required more than basic compilation and grouping.

As noted in Section 1.2 of the main report, BGC engaged with Sage Team working groups through a series of meetings facilitated by working group co-chairs. During these meetings, BGC presented the aspects of the asset data model that were relevant to each group and solicited feedback. A tracking sheet is on file with Sage on Earth where working groups were asked to provide feedback for consideration in the data model. Table A-3-1 summarizes the assets considered for each hazard type. This table denotes an asset considered for a given hazard with a check mark; a blank cell indicates that an asset was not considered for that hazard type. Appendix C provides more detailed breakdown of each asset and the units used to measure level of exposure (e.g. count, area, length, value). Appendix D lists data sources.

As shown in Table A-3-1, all assets were considered for flood and wildfire hazard exposure analysis. For extreme heat, the hazard criteria reflect Environment and Climate Change Canada (ECCC)'s heat warning threshold for population (ECCC, 2023), and thus exposure is quantified only for population. Drought exposure was only quantified for populations and environmental assets. For both heat and drought, patterns of drought illustrated by the hazard exposure maps may inform broader, qualitative examination of drought exposure across BC than the assets directly considered. For seismic, different hazard sub-types were considered for specific asset types, with the results combined to deliver a hazard exposure analysis considering all asset types.

Table A-3-1 Assets considered for hazard exposure analysis.

Hazard Information			Assets Considered								
Hazard Group	**Hazard Process**	**Definition**	**Population**	**Built-Form**	**Critical Facilities**	**Businesses**	**Environmental Values**	**Roads and Railways**	**Petroleum Infrastructure**	**Electrical and Communication Infrastructure**	**Water and Sanitary Infrastructure**
Seismic	Ground Shaking	Areas exceeding peak ground acceleration (PGA) of 0.09 g for a 1 in 2475-year earthquake shaking scenario	✓	✓	✓	✓					
		Areas exceeding PGA of 0.28 g for a 1 in 2475-year earthquake shaking scenario						✓		✓	
		Areas exceeding peak ground velocity (PGV) of 125 mm/s for a 1 in 2475-year earthquake shaking scenario							✓		
		Areas exceeding PGV of 250 mm/s for a 1 in 2475-year earthquake shaking scenario									✓
	Liquefaction	Areas with potentially liquefiable soils and exceeding PGA of 0.09g for a 1 in 2475-year earthquake shaking scenario	✓	✓	✓	✓		✓	✓	✓	✓
	Co-seismic Landslides	Areas where the PGA for the 1 in 2475-year earthquake shaking scenario exceeds a slope's critical acceleration	✓	✓	✓	✓		✓	✓	✓	✓
Flooding	Riverine Flood Hazards	Areas with potential riverine flood inundation for a 1 in 200 annual probability of exceedance (>10 km^2 catchments)	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Coastal Flood Hazards (Baseline)	Coastal flood elevation including sea level rise (2020) + mean higher high water (MHHW) + Storm Surge (Hindcast, 99^{th} Percentile, 2000 to 2020)	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Coastal Flood Hazards (Climate Change)	Coastal flood elevation including sea level rise (2100) + mean higher high water + Storm Surge (Multi-model Maximum, 2080 to 2099)	✓	✓	✓	✓	✓	✓	✓	✓	✓
Wildfire	Wildfire	Areas where the 2021 Provincial Strategic Threat Analysis (PSTA) Wildfire Threat Rating is ≥6 (Moderate)	✓	✓	✓	✓	✓	✓	✓	✓	✓
Climate	Extreme Heat (Baseline)	Areas where the 50-year return period 3-day average daily mean (1971-2000) temperature exceeds the average Environment and Climate Change Canada's (ECCC's) heat warning threshold (average of daytime maximum and overnight minimum temperature) for a given heat warning region	✓								
	Extreme Heat (Climate Change)	Areas where the 50-year return period 3-day average daily mean (2041-2070, SSP5-8.5 emission scenario exceeds the average ECCC's heat warning threshold (average of daytime maximum and overnight minimum temperature) for a given heat warning region									
	Drought (Baseline)	Areas where the 50-year return period 12-month Standardized Precipitation Evapotranspiration Index (SPEI) value (1981-2010, median of 25 global climate models assuming SSP5-8.5) exceeds the threshold for extreme drought (SPEI<-2)	✓				✓				
	Drought (Climate Change)	Areas where the 50-year return period 12-month Standardized Precipitation Evapotranspiration Index (SPEI) value (2021-2050, median of 25 global climate models assuming SSP5-8.5) exceeds the threshold for extreme drought (SPEI<-2)	✓				✓				

A-3.2 Built Form

BC Assessment data includes characterization of "land improvements" (Built Form) associated with each titled property in ParcelMap BC, and is regularly maintained and updated[2]. Additional data preparation was required for Built Form data prior to carrying out hazard exposure analysis. Built-form assets are represented by the ParcelMap BC cadastral fabric joined with BC Assessment data. ParcelMap BC represents titled and Crown land parcels as polygons across BC.

Every registered title ("roll number") in BC is associated with a parcel polygon. This means that the combination of rolls and parcels enables province-wide characterization of use-type and assessed value for Built Form province-wide, at parcel resolution.

Where buildings contain multiple titled units, polygons are stacked on top of each other (e.g., a 500-unit strata unit tower would be represented by 500 polygons on top of each other, each attributed with data unique to the Roll number). To increase the performance of large data operations for province-wide hazard exposure analysis, the stacked polygons were collapsed into a single polygon, attributed according to its primary actual use and total (summed) assessment value. For clarity, BGC's analysis considered improvement value, and did not consider land value.

BGC notes uncertainties with Built Form data noted in Appendix B. BC Assessment data is not available at the resolution of individual building footprints and does not include parcel data for First Nations reserve lands. Assessed value of Built Form do not necessarily reflect their replacement value if destroyed in a disaster (e.g., the cost to replace a depreciated Built Form may be higher than its assessed value). Appendix B discusses implications of these uncertainties and opportunities to resolve at a subsequent project stage.

A-3.3 Built Form (First Nations Reserves)

BC Assessment data does not include unassessed Built Form on First Nations reserve lands. On reserve lands, BGC relied on building replacement values estimated by NRCan (2022b) in their physical, settled areas layer, which includes estimated total building replacement values within a given polygon. BGC proportioned building replacement value according to area (e.g., if half of a First Nations reserve intersected a settled area polygon, half of the building replacement value would be assigned to the reserve). In summary, estimates of built form value on First Nations reserves are based on lower resolution data inputs and contain higher uncertainty than in areas covered by BC Assessment data.

BGC notes uncertainties with Critical Facilities data noted in Appendix B. In summary, replacement values should not be considered equivalent to assessed values, and are not categorized by Built Form type. In a 2022 assessment outside of the DCRRA project, BGC completed select quality control of NRCan (2022b) Built Form values for First Nation reserve areas in Squamish-Lillooet Regional District, based on comparison of the number of visible

[2] Data for this assessment was accessed by EMCR on October 20, 2023.

building footprints to the number of buildings NRCan's data set reports for an area (BGC, April 24, 2023). In summary, NRCan's estimated number of buildings generally matched observations, but BGC did find several cases where structures were undercounted by up to 30%. Given that the NRCan inventory is not actively maintained, it should be considered a lower bound estimate.

A-3.4 Critical Facilities

Critical facilities were defined as facilities that are important in terms of their continued function during an emergency (as opposed to, for example, their monetary value). These may include facilities that:

- Provide vital services in saving and avoiding loss of human life
- Accommodate and support activities important to rescue and treatment operations
- Are required for the maintenance of public order
- Confine activities or products that, if disturbed or damaged, could be hazardous to the region.

The critical facility inventory includes Built Form at single locations. Critical facilities were classified according to categories and criteria shown in Table A-3-2, using BC Assessment primary actual descriptions, and placed at the centroid of a given parcel. BGC additionally incorporated critical facility locations manually checked during regional risk assessments by BGC for the Squamish-Lillooet Regional District (April 24, 2023), Thompson Nicola Regional District (June 4, 2021), and Regional District of Central Kootenay (March 31, 2019).

BGC notes uncertainties with Critical Facilities data noted in Appendix B. Because the data are sourced from BC Assessment, they do not include First Nations reserve lands, and do not contain an identifier that can be related to specific building footprints within a parcel. Additional critical facilities may exist that require local knowledge to identify (e.g., a facility used by a community to store emergency response resources). Given the source of data, a key gap includes the inclusion of facilities critical for reasons related to cultural importance.

Table A-3-2 Critical facility categories and Built Form within each category.

Critical Facility Category	Facility Types Included[1]
Emergency Response Services	Emergency Operations Center, Government Buildings (Offices, Fire Stations, Ambulance Stations, Police Stations).
Emergency Response Resources	Asphalt Plants, Concrete Mixing, Oil & Gas Pumping & Compressor Station, Oil & Gas Transportation Pipelines, Petroleum Bulk Plants, Works Yards.
Utilities	Electrical Power Systems, Gas Distribution Systems, Water Distribution Systems, Hydrocarbon Storage.
Communication	Telecommunications.
Medical Facilities	Hospitals, Group Home, Seniors Independent & Assisted Living, Seniors Licenses Care.
Transportation	Airports, Heliports, Marine & Navigational Facilities, Marine Facilities (Marina), Service Station.
Environmental	Garbage Dumps, Sanitary Fills, Sewer Lagoons, Liquid Gas Storage Plants, Pulp & Paper Mills.
Community	Government Buildings, Hall (Community, Lodge, Club, Etc.), Recreational & Cultural Buildings, Schools & Universities, College or Technical Schools.
Food	Greenhouse, Poultry House

Note:

1. BC Assessment primary actual use code descriptions.

A-4 SEISMIC HAZARDS

A-4.1 Hazard Definition

Seismic hazards considered in this project are the direct effects of ground motion and ground failure (liquefaction and landslides) caused by an earthquake. Ground failure is permanent ground displacement caused by strong shaking, which can occur by liquefaction-induced failures and landsliding. For the provincial-scale hazard exposure analysis, seismic hazards are based on 1:2475-year return period ground motions (2% chance of exceedance in 50 years) from Canada's sixth-generation seismic hazard model (Kolaj et al., 2023). The 1:2475-year return period earthquake is the design earthquake for building structures adopted by the National Building Code of Canada. We use the term "earthquake shaking scenario" to describe a ground shaking level that has a return period of 2475 years (or a probability of exceedance of 2% in 50 years). Specific earthquake scenarios were not considered.

A-4.1.1 Ground Motion

Ground motion is the transient shaking felt at earth's surface as seismic waves pass by. This shaking can threaten assets depending on the shaking intensity and asset type. Ground motions generally increase with earthquake magnitude, decrease with distance to the source, and depend on the style of faulting, the position of the site with respect to the relative motion between blocks, the stiffness of rock between the source and site, and site soil and topographic conditions. Although there are many metrics to quantify shaking intensity, BGC has selected peak ground acceleration (PGA) and peak ground velocity (PGV) for the provincial-scale hazard exposure analysis.

PGA greater than 0.09 g was used as a hazard exposure indicator for the “Built Form” (e.g., buildings) and anything contained by or related to the Built Form, such as population, critical facilities, and businesses (Table A-3-1). PGA of 0.09 g roughly corresponds to a VI (Strong) on the Modified Mercalli Intensity (MMI) scale[3], which is the level of ground shaking expected to start causing some building damage.

PGA greater than 0.28 g was used as a hazard exposure indicator for surface infrastructure, such as roads, rail, and electrical or communication utilities (Table A-3-1). PGA of 0.28 g roughly corresponds to a VII (Very Strong) on the MMI scale[2].

PGV values were used as exposure indicators for buried infrastructure following work by Warman et al. (2018) for screening pipelines following earthquakes. PGV greater than 125 mm/s was used as an exposure indicator for brittle pipe (typically segmented) such as water pipelines (Table A-3-1). PGV greater than 250 mm/s was used as a exposure indicator for ductile pipe (arc-welded steel) such as oil and gas pipelines (Table A-3-1).

A-4.1.2 Liquefaction

Liquefaction is the sudden loss of soil strength whereby certain soils behave as liquids upon ground shaking. Soils susceptible to liquefaction are loose, cohesionless, and saturated. Upon shaking, liquefiable soils may experience collapse and elevated pore pressures, causing the soil to temporarily lose its strength and liquefy. Liquefaction and can cause ground failure through lateral spreads, flow slides, and loss of the ground’s bearing capacity, threatening assets. For the provincial-scale hazard threat analysis, assets threatened by liquefaction are those that intersect potentially liquefiable soils with ground motions exceeding a PGA of 0.09 g (Santucci de Magistris et al., 2013).

A-4.1.3 Coseismic Landslides

Coseismic landslides are the movement of rock, soil, or debris down a slope triggered by ground shaking, threatening assets in their paths. A slope’s critical acceleration is a theoretical horizontal acceleration required to reduce the factor of safety of a slope below unity, assuming an infinite slope process with a nominal 3 m depth. Critical acceleration is a function of the strength of the underlying geology, slope angle, saturation, and landslide mechanism. For the provincial-scale hazard threat analysis, assets threatened by coseismic landslide intersect slopes where ground motions from the 2475-year return period earthquake exceed a slope’s critical acceleration.

[3] Based on the United States Geological Survey PGA to MMI scale conversion for California (Wald et al., 1999).

A-4.2 Data Inputs

A-4.2.1 Sixth-Generation Seismic Hazard Model of Canada

Table A-4-1 lists data inputs and clarifies their application to develop the hazard layers described in Section A-4.3.

Table A-4-1 Hazard data inputs.

Type	Application	Item	Description
Sixth-generation seismic hazard model of Canada	Ground motion hazard	Source	Kolaj, M., Halchuk, S., & Adams, J. (2023)
		Spatial Resolution	Grid points vary from 3-150 km spacing, approximately 20 km on average
		Spatial Data Format	.csv
Surficial Geology	Ground motion hazard; Liquefaction hazard, Landslide hazard	Source	Geological Survey of Canada (2014)
		Spatial Resolution	1:5,000,000
		Spatial Data Format	Vector
Floodplain Mapping	Liquefaction hazard; Coseismic landslide hazard	Source	See Section A-5 of this appendix.
		Spatial Resolution	30 m
		Spatial Data Format	Vector
Bedrock Geology	Ground motion hazard; Coseismic landslide hazard	Source	Cui, Y., Miller, D., Schiarizza, P., & Diakow, L.J. (2017)
		Spatial Resolution	1:50,000 to 1:250,000
		Spatial Data Format	Vector
Topography	Ground motion hazard; Liquefaction hazard; Coseismic landslide hazard	Source	Copernicus DEM – Global and European Digital Elevation Model, GLO-30, ESA
		Spatial Resolution	30 m
		Spatial Data Format	Raster

A-4.3 Hazard Layer Development

A-4.3.1 Ground Motion Hazard Layer

BGC prepared the ground motion hazard data by:

- Interpolating contiguous 50 m grids of PGA and PGV for each site class from points from Canada's sixth-generation seismic hazard model (Kolaj et al., 2023) for the 2475-year return period earthquake
- Assigning PGA and PGV for the corresponding site class based on geologic classification (described in A-4.3.1.1)
- Correcting PGA for topographic amplification (described in A-4.3.1.2).

A-4.3.1.1 Site Class

Ground motions can be amplified or de-amplified depending on the stiffness of the underlying material and the ground shaking intensity. The sixth-generation seismic hazard model (Kolaj et al., 2023) accounts for this by providing ground motions for various site classes related to the time-averaged shear wave velocity in the upper 30 meters of the ground (Table A-4-2). Site classes were associated to available province-wide surficial geology (Table A-4-3) and bedrock geology (Table A-4-4) polygons using the descriptions provided by the Building Seismic Safety Council (BSSC) (1994) (Table A-4-2). Site classification was based on surficial geology if present, and bedrock geology in locations without surficial geology or the "Bedrock – Undifferentiated" description. This methodology is in general conformance with a "Level 1" seismic microzonation map, as defined by Engineers and Geoscientists BC (EGBC) 2024 seismic microzonation mapping guideline.

Table A-4-2 Seismic site class definition from BSSC (1994).

Site Class	Definition	Geologic Description
A	V_{S30} > 1500 m/s	Hard rock
B	760 < V_{S30} <= 1500 m/s	Rock
C	360 < V_{S30} <= 760 m/s	Very dense soil and soft rock
D	180 < V_{S30} <= 360 m/s	Stiff soil
E	V_{S30} < 180 m/s	Soft soil
F[1]	Site-specific evaluation required	Liquefiable, sensitive, collapsible, or prone to failure under seismic loading

Notes:

1. Site Class F not applicable in the provincial hazard exposure analysis.
2. V_{S30} is time-averaged shear wave velocity in the uppermost 30 m of the rock/soil profile. In a profile with layers of variable shear wave velocity, V_{S30} is a weighted average based on the time spent by shear waves in passing through each layer.

Table A-4-3 Seismic site class assigned to surficial geology mapping (GSC, 2014).

Surficial Geology	Site Class
Glacial sediments - Blanket	D
Alluvial sediments - Undifferentiated sediments	D
Bedrock - Undifferentiated	See Table A-4-4
Colluvial and mass-wasting deposits - Undifferentiated deposits	D
Colluvial and mass-wasting deposits - Veneer	C
Glacial Ice or Snowpack - Snowpacks	C
Glacial sediments - Veneer[1]	C
Glaciofluvial sediments - Ice-contact sediments	D
Glaciofluvial sediments - Outwash plain sediments	D
Glaciolacustrine sediments - Littoral and nearshore sediments	D
Glaciolacustrine sediments - Offshore sediments	D
Glaciomarine sediments - Littoral and nearshore sediments	D
Glaciomarine sediments - Offshore sediments	D
Glaciomarine sediments – Veneer[1]	C
Marine sediments - Offshore sediments	D
Organic deposits - Undifferentiated deposits	E
Volcanic deposits - Undifferentiated	D

Note:

1. Site class assumes veneers are underlain by bedrock.

Table A-4-4 Seismic site class assigned to British Columbia bedrock geology mapping (Cui et al., 2017).

Bedrock Geology[1]	Assigned Site Class
Sedimentary rocks	B
Intrusive rocks	A
Volcanic rocks	B
Ultramafic rocks	A
Metamorphic rocks	A
Volcanic and sedimentary rocks	B
Subvolcanic intrusions	A
Sedimentary and volcanic rocks	B
Unknown	B
Mafic volcanic rocks	B
Land surface feature	C

Note:

1. From British Columbia bedrock geology “rock class” field.

A-4.3.1.2 Topographic Amplification

Seismic waves can be amplified or de-amplified when the surface topography causes focusing or scattering of propagating waves. To account for topographic effects, PGA from the 50 m gridded seismic hazard model was multiplied by 1.3 for slopes between 10 and 30 degrees, and by 1.5 where the slope exceeds 30 degrees (Ashford & Sitar, 2002; Bray & Macedo, 2019). Slope data is from the Copernicus 30 m (GLO-30) digital elevation model (DEM).

A-4.3.2 Liquefaction Hazard Layer

BGC created a liquefaction hazard layer using available province-wide data based on the presence of liquefiable soils (loose, cohesionless, saturated) and a ground motion threshold large enough to cause soil particle rearrangement (PGA of 0.09 g assumed). The methodology applied is in general conformance with a “Level 1” seismic microzonation map, as defined by Engineers and Geoscientists BC (EGBC) 2024 seismic microzonation mapping guideline.

The presence of liquefiable soils was based on classifications from Youd & Perkins (1978), which qualitatively rates liquefaction susceptibility of saturated soils using the age and genesis of surficial deposits. Surficial geology units from the Surficial Geology of Canada map (GSC, 2014) were classified as liquefiable by relating the description to the Youd & Perkins (1978) classification for “High” and “Very High” liquefaction susceptibility with strong shaking (Table A-4-5). In addition to the surficial geology layer, the 200-year floodplain layer (Section A-5) was used to identify potentially saturated and liquefiable soils along modern floodplains, adding detail to the Surficial Geology of Canada map (GSC, 2014) which does not have the resolution to include these landform.

In the absence of saturation data across the province, all liquefiable soils on slopes less than 3 degrees were assumed to be potentially saturated at this stage of the provincial hazard exposure analysis. Slope data is from the Copernicus 30 m (GLO-30) DEM. The 3-degree threshold is intended to identify areas where water may accumulate and filter out steep creeks in the 200-year floodplain layer. It is based on the Church (2022) definition of a steep headwater channel, in which channels (if not bound by bedrock) have beds and banks composed of larger clasts which are less susceptible to liquefaction.

In summary, BGC prepared the liquefaction hazard data by:

- Classifying surficial geology as liquefiable based on Table A-4-5 and converting to a 30 m grid (same as Copernicus 30 m (GLO-30) DEM), including any grid cells within the 200-year floodplain layer as liquefiable
- Including any grid cells that have a slope of less than 3 degrees from the Copernicus 30 m (GLO-30) DEM and a PGA from the ground motion hazard data (Section A-4.3.1) greater than 0.09 g as the liquefaction hazard layer.

Table A-4-5 Liquefaction susceptibility assigned to surficial geology mapping (GSC, 2014).

Surficial Geology	Liquefiable[1]
Glacial sediments - Blanket	No
Alluvial sediments - Undifferentiated sediments	Yes
Bedrock - Undifferentiated	No
Colluvial and mass-wasting deposits - Undifferentiated deposits	Yes
Colluvial and mass-wasting deposits - Veneer	No
Glacial Ice or Snowpack - Snowpacks	No
Glacial sediments - Veneer	No
Glaciofluvial sediments - Ice-contact sediments	No
Glaciofluvial sediments - Outwash plain sediments	No
Glaciolacustrine sediments - Littoral and nearshore sediments	Yes
Glaciolacustrine sediments - Offshore sediments	No
Glaciomarine sediments - Littoral and nearshore sediments	Yes
Glaciomarine sediments - Offshore sediments	Yes
Glaciomarine sediments - Veneer	No
Marine sediments - Offshore sediments	Yes
Organic deposits - Undifferentiated deposits	No
Volcanic deposits - Undifferentiated	No

Note:

1. Based on Youd & Perkins (1978) “High” or “Very High” liquefaction susceptibility classification for strong seismic shaking based on the age and genesis of surficial deposits when saturated.

A-4.3.3 Coseismic Landslide Hazard Layer

BGC based coseismic landslide susceptibility on the presence of slopes where 1:2475 ground motion exceeds a critical acceleration (Ac) threshold estimated based on ground strength, saturation, slope angle, and assumed mechanism, employing generalized relationships developed by Wieczoriek et al. (1985) and Wilson and Keefer (1985) for shallow translational (i.e., infinite-slope) rock and earth slides. FEMA (2020) and the State of Oregon (Oregon Department of Geology and Mineral Industries, 2019) have adopted this methodology for regional earthquake hazard mapping. The methodology applied is in general conformance with a “Level 1” seismic microzonation map, as defined by Engineers and Geoscientists BC (EGBC) 2024 seismic microzonation mapping guideline. It is a simplified approach based on the infinite slope equation applied to landslide processes such as debris slides and debris avalanches. The methodology is not is not intended to capture rock falls, rapid rock slides, rock avalanches, deep-seated landslides, or existing landslides that become reactivated upon shaking. Furthermore, the approach only identifies potential locations of instability, and does not include landslide runout or retrogression.

Wieczoriek et al. (1985) and Wilson & Keefer (1985) related critical acceleration, Ac, to geologic group, saturation (wet or dry), and slope angle (Figure A-4-1). For the provincial hazard exposure analysis, saturation is based on the presence of the 200-year floodplain layer (Section A-5) and slope angle is derived from the Copernicus 30 m (GLO-30) DEM. Three geologic groups generalized from Wieczorek et al. (1985) were used to characterize the shear strength of rock and soils:

- Group A: strongly cemented rocks
- Group B: weakly cemented rocks and soils (typical rock mass strength with an equivalent friction angle 35°)
- Group C: argillaceous rocks and soils, including existing landslides in soil and weak rock (typical friction angle 20° or less).

These geologic groups were assigned to available province-wide surficial geology (Table A-4-6) and bedrock geology (Table A-4-7) units. Geologic group assignment was based on surficial geology if present, and bedrock geology in locations without surficial geology or the "Bedrock – Undifferentiated" description.

In summary, BGC prepared the coseismic landslide hazard data by:

- Classifying geology layers as Group A, B, or C based on Table A-4-6 and Table A-4-7 and converting to a 30 m grid (same as Copernicus 30 m (GLO-30) DEM)
- Using the relationships in Figure A-4-1, calculating Ac at each grid cell based on geologic group, slope angle from the Copernicus 30 m (GLO-30) DEM, and presence/absence of 200-year floodplain layer (wet/dry)
- Including any grid cells where PGA from the ground motion hazard data (Section A-4.3.1) is greater than Ac as the coseismic hazard layer.

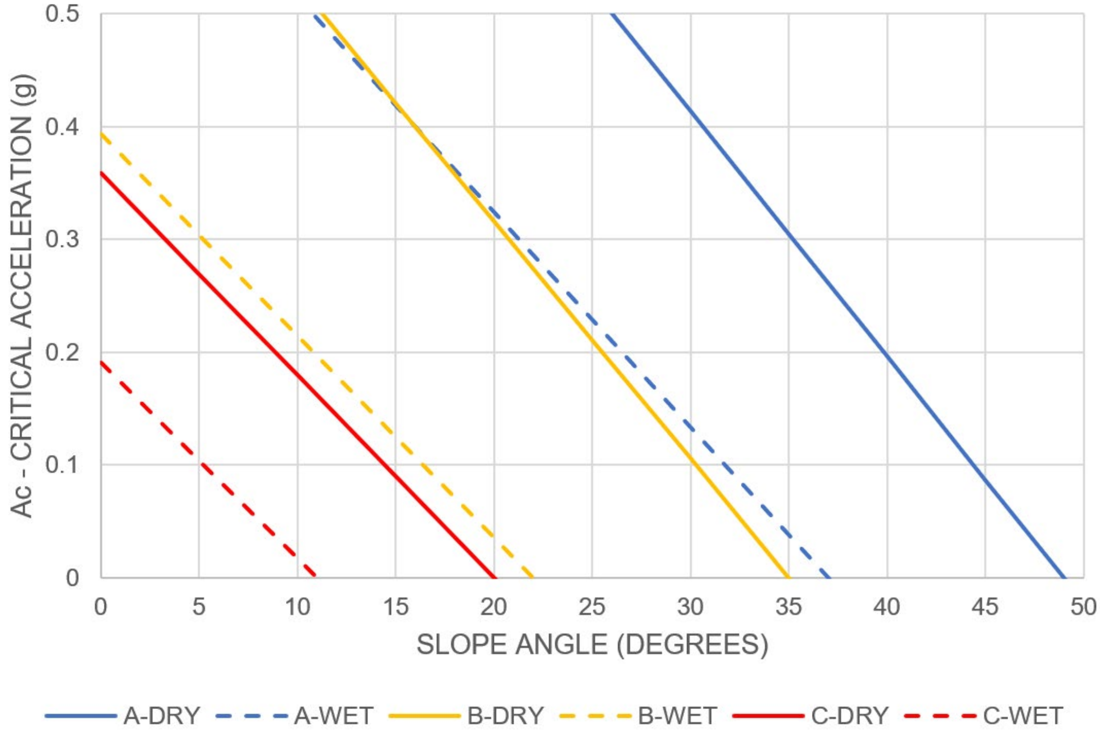


Figure A-4-1 Critical acceleration (Ac) related to geologic groups (A, B, C), slope angle, and saturation (dry, wet).

Table A-4-6 Geologic group (Wieczorek et al., 1985) assigned to surficial geology mapping (GSC, 2014).

Surficial Geology	Assigned Geologic Group
Glacial sediments - Blanket	B
Alluvial sediments - Undifferentiated sediments	B
Bedrock - Undifferentiated	See Table A-4-4
Colluvial and mass-wasting deposits - Undifferentiated deposits	C
Colluvial and mass-wasting deposits - Veneer	C
Glacial ice or snowpack - Snowpacks	C
Glacial sediments - Veneer	B
Glaciofluvial sediments - Ice-contact sediments	B
Glaciofluvial sediments - Outwash plain sediments	B
Glaciolacustrine sediments - Littoral and nearshore sediments	B
Glaciolacustrine sediments - Offshore sediments	C
Glaciomarine sediments - Littoral and nearshore sediments	B
Glaciomarine sediments - Offshore sediments	C
Glaciomarine sediments - Veneer	C
Marine sediments - Offshore sediments	C
Organic deposits - Undifferentiated deposits	C
Volcanic deposits - Undifferentiated	B

Table A-4-7 Geologic group (based on classification from Wieczorek et al., 1985) assigned to British Columbia bedrock geology mapping (Cui et al., 2017).

Bedrock Geology[1]	Assigned Geologic Group
Sedimentary rocks	A (C if "shale", "argillite", or "coal" in rock type or unit description field)
Intrusive rocks	A
Volcanic rocks	B
Ultramafic rocks	A
Metamorphic rocks	A
Volcanic and sedimentary rocks	A (C if "shale", "argillite", or "coal" in rock type or unit description field)
Subvolcanic intrusions	A
Sedimentary and volcanic rocks	A (C if "shale", "argillite", or "coal" in rock type or unit description field)
Unknown	A
Mafic volcanic rocks	A
Land surface feature	B

Note:

1. From British Columbia bedrock geology “rock class” field.

A-4.4 Hazard Exposure Analysis Logic

Ground shaking, liquefaction, and coseismic landslide hazard layers are combined to comprise the “seismic” hazard layer used as an input to the hazard exposure analysis. Given these hazards may impact different assets in different ways, the hazard exposure analysis only includes relevant assets for each hazard type and threshold (Table A-3-1). If any of the thresholds are met for the relevant asset, the asset is considered “exposed”.

A-4.5 Gaps and Limitations

The following list summarizes gaps and limitations specific to the seismic hazard layer development and exposure analysis:

- The ground motion hazard layer is based on simplified criteria and is not intended to represent this hazard at any level more detailed than a provincial scale. The ground motion hazard layer is limited by the data quality of the sixth-generation seismic hazard model (Kolaj et al., 2023). The spacing of the data points from this model vary, and the gridded interpolation required for the hazard exposure analysis may not accurately represent ground motions far from these points. The site classification is based on province-wide low-resolution geologic mapping related to general geologic descriptions, and may therefore be inaccurate at a given location. Topographic amplification is based on simplified criteria and is limited by the accuracy of the available slope DEM.
- The liquefaction hazard layer is based on simplified criteria and is not intended to represent this hazard at any level more detailed than a provincial scale. It is based on

simplified associations of low-resolution province-wide surficial geology mapping to a typical age and genesis of material used to estimate liquefaction susceptibility. The layer is also limited by ground saturation assumptions and the accuracy of the available slope DEM. Thee coseismic landslide hazard layer is based on simplified criteria. Without further refinement, it is not intended to represent this hazard at any level more detailed than a provincial scale. It is based on simplified associations of low-resolution province-wide geologic mapping to a general rock strength class. The layer is also limited by ground saturation assumptions and the accuracy of the available slope DEM.

- Furthermore, the coseismic landslide hazard layer only includes locations where ground motions may initiate instability but does not include any information on the size of the landslide or landslide runout. Landslide size and runout is an important factor in hazard exposure analysis, especially in the case of earthquake-triggered rock avalanches with far-reaching destruction. Lastly, the methodology used to identify coseismic hazards is not "tuned" to landslide processes such as to rock falls, rapid rock slides, rock avalanches, deep-seated landslides, or existing landslides that become reactivated upon shaking.
- The DCRRA Seismic Working Group supporting this project has flagged that damage correlation with PGA for many structures is poor, recommending other metrics such as various spectral accelerations periods (email from Tuna Onur on behalf of the Seismic Working Group, personal communication, February 26, 2024). Future work may include different ground motion intensity metrics and relevant thresholds (see next point).
- The PGA and PGV threshold values for ground motion are imperfect, simplistic, and uncertain. Although they may be adequate to reflect general counts of threatened assets at provincial scale, they are inaccurate for any specific asset. Future work may refine these threshold values using fragility and vulnerability functions specific to asset sub-types (e.g., reinforced concrete vs. wood-frame structures). Furthermore, thresholds treat the hazard exposure as a binary (exposed or not), so the hazard exposure analysis does not include the degree of damage or damage uncertainty (e.g., probability of loss). Future work may find ways to incorporate the results from the national seismic risk model for Canada (Hobbs et al., 2023) that apply fragility and vulnerability models to estimate probability of building damage and loss (economic, life loss).
- Only one earthquake shaking scenario (return period) was included in the hazard exposure analysis, consistent with the other hazards. The 1:2475-year earthquake shaking scenario recommended by the DCRRA Seismic Working Group has regulatory implications as it is the design earthquake for the National Building Code of Canada but may overrepresent asset counts especially if compared to others hazards with lower return period thresholds (e.g., 1:200-year floodplain layer for riverine flooding hazards). Multiple earthquake shaking scenarios should be evaluated, as recommended by the DCRRA Seismic Working Group.
- The hazard exposure analysis does not incorporate existing seismic microzonation work that has been completed at a detailed level, such as for the city of Metro Vancouver. Incorporating such work may improve the accuracy of the hazard exposure analysis, especially for populated areas with many assets.

A summary of these gaps and limitations with considerations to resolve is provided in Appendix B.

A-5 RIVERINE FLOODS

A-5.1 Hazard Definition

Flood hazard is defined for exposure analysis as areas with potential riverine flood inundation for a 200-year flood event (0.5% annual exceedance probability, AEP).

A-5.2 Data Inputs

BGC developed a province-wide Tier 1 floodplain layer for BC Hydro, which was shared with the Province and used as the basis for flood hazard exposure analysis (April 19, 2024). The key data inputs used to develop the Tier 1 floodplain mapping layer are summarised in Table A-5-1 including terrain, flow and water level data, and hydrographic features.

Table A-5-1 Summary of key data inputs.

Data Type	Description	Reference
Terrain	The COP-30 dataset has global coverage, at 30 m resolution in Cananda, with an absolute vertical accuracy of <4 m and an absolute horizontal accuracy of < 6 m. This dataset comes from the TanDEM-X satellite mission (2011 to 2015).	**Copernicus**
Mean Daily Peak Flows	Annual maxima mean daily peaks flows were downloaded for analysis of the 200-year flood at each hydrometric station. The watershed area reported by these organisations was used in the analysis.	**WSC** and **USGS**
Water Level	Mean daily water levels and discharge values were downloaded for rating curve development at each hydrometric station.	**WSC** and **USGS**
Waterbodies	The hydrographic features in this dataset include waterbodies (e.g., lakes) that were used to merge with the Tier 1 floodplain map.	**CanVec**

A-5.3 Hazard Layer Development

BGC used the empirical approach “Global Floodplain” (GFPLAIN) by Nardi et al. (2019) as an efficient process to simulate floodplains over large areas, compared to methods optimized for detailed, smaller area assessment (e.g., hydraulic-based methods). The selected method relies on an empirical model that relates flood depth to watershed area using the following equation, where *a* and *b* are constant coefficients [Eq. 1].

$$Flood\ Depth = a(Watershed\ Area)^b \quad \text{[Eq. 1]}$$

BGC advanced this method by developing regional coefficients to capture the diversity of BC across six ecozones (Figure A-5-1) (NRCan 2010). Table A-5-2 summarizes the 687 WSC and USGS hydrometric stations used for analysis, which are distributed in each ecozone.

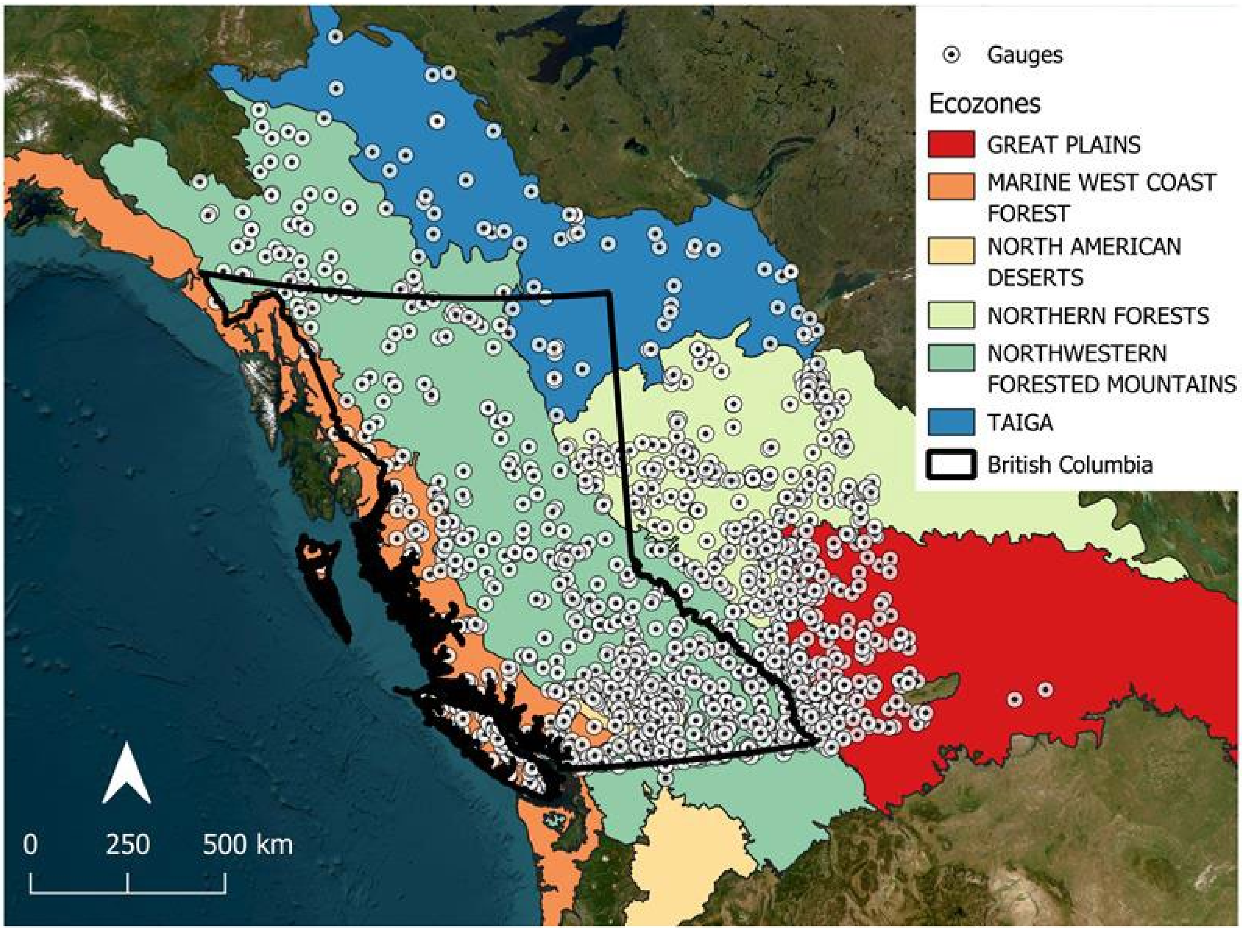


Figure A-5-1 Ecozones of BC.

Table A-5-2 Number of hydrometric stations analyzed in each ecozone.

ID	Ecozone	Number of Hydrometric Stations
1	Marine West Coast Forest	109
2	North American Desserts	69
3	Northern Forests	145
4	Northwestern Forested Mountains	212
5	Taiga	38
6	Great Plains	114

The 200-year flood was estimated for each ecozone using a flood frequency analysis (FFA). The FFA was based on the Annual Maxima Series (AMS) using the mean daily flow at every hydrometric station present in the six ecoregions. The minimum record length recorded at the gauge for use in the FFA was 10 years. The Generalised Extreme Value (GEV) distribution was fit to the AMS using the linear moments for parameter estimation (Zhang et al., 2019).

The water depth corresponding to the 200-year flood was estimated using a rating curve to relate water depth to streamflow. The rating curve is defined by a power law developed at each hydrometric station in the six ecoregions. An example of a rating curve for the Pack River at the Outlet of McLeod Lake (07EE010) hydrometric station located in the Northwestern Forested Mountains ecoregion is shown in Figure A-5-2(a). In some cases, there was noise in the stage data for lower discharge values as shown in Figure A-5-2(b). The lower 10% of the discharge values and corresponding stage values were removed from the dataset to improve the power law fit for the higher discharge values.

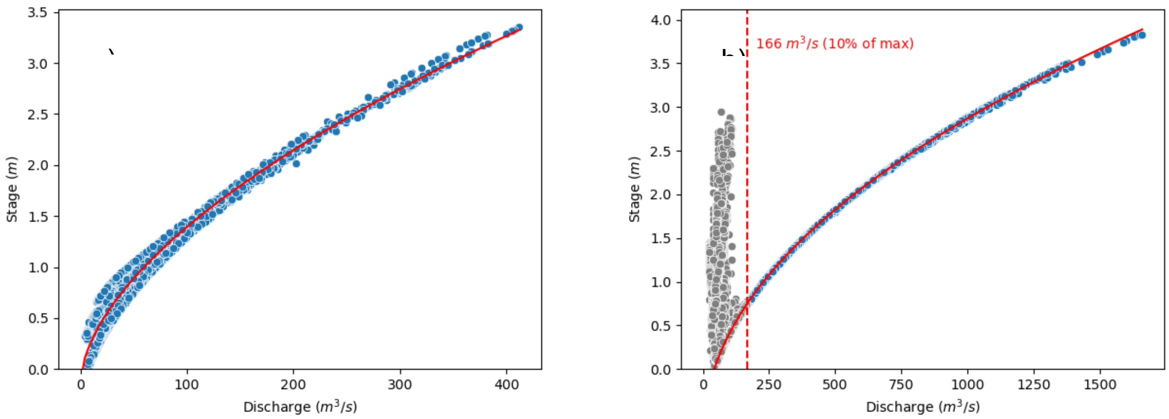


Figure A-5-2 Example rating curve for a) Pack River at the Outlet of McLeod Lake (07EE010) hydrometric station and b) Finlay River above Alie River (07EA005) hydrometric station. Both stations are in the Northwestern Forested Mountains ecoregion. Gray circles show data points removed from the analysis.

The water depth corresponding to the 200-year flood and watershed area at each hydrometric station was subsequently used for the development of the regional coefficients within each ecoregion. The watershed area upstream of each hydrometric station is based on the published value provided by WSC or USGS.

Terrain analysis techniques were used to extract the stream network (in raster form) from the Copernicus 30 m DEM. Each stream network grid cell was assigned a flood depth using the watershed area based on the regional equation associated with a ecoregion. This algorithm produces a gridded floodplain by identifying low-lying grid cells along a watercourse (Figure A-5-3). The floodplain extent is formed by the grid cells that are characterised by ground elevations that are lower than the corresponding flood elevation. The flood elevation is defined as the grid cell ground elevation plus the flood depth, expressed in meters.

The Python script and user manual of the GFPLAIN algorithm used for generating the Tier 1 floodplain map is accessible at https://github.com/fnardi/GFPLAIN with instructions for applications and reuse of the code.

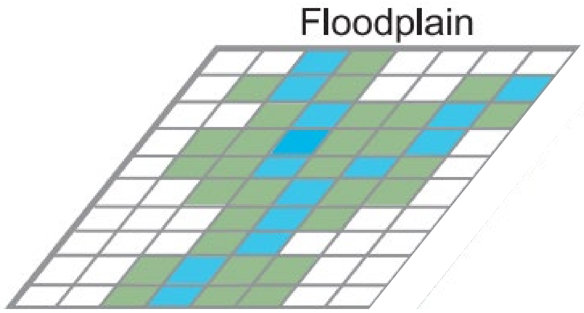


Figure A-5-3 Conceptual model of the gridded layer that is derived by defining grids as floodplain whose elevations are lower than the corresponding stream network flow levels. Blue depicts inundated cells while green shows non-inundated grid cells along a stream segment (Nardi et al., 2019).

The GFPLAIN methodology weakens in valley bottoms given the lack of topographic relief in these low-lying areas. These low-lying areas can include the presence of lakes and wetlands. As such, the CanVec database of waterbodies was merged with the Tier 1 floodplain to distinguish with watercourses. Each grid cell was assigned a unique identifier as per Table A-5-3. The floodplain results include a raster mask where 0=not flooded, 1=flooded, and 2 =waterbody (Figure A-5-4).

Table A-5-3 Grid cell identifier and description.

Identifier	Description
0	Grid not considered flooded due to riverine, clearwater flooding.
1	Grid considered flooded due to riverine, clearwater flooding.
2	Grid considered to be a waterbody.

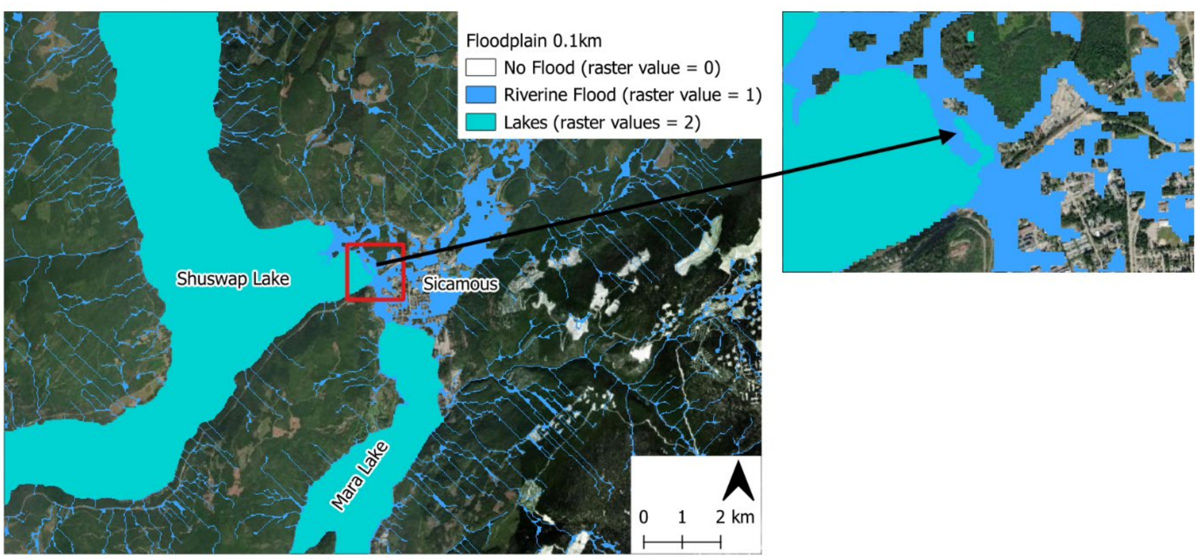


Figure A-5-4 Example of area where waterbodies were merged with the Tier 1 floodplain map.

A-5.4 Hazard Exposure Analysis Logic

The hazard exposure analysis methodology was applied for riverine flooding as described in Section A-2 for all assets.

A-5.5 Gaps and Limitations

Gaps and limitations of Tier 1 floodplain mapping are described in BGC (April 19, 2024) and Appendix B. BGC notes that the Tier 1 floodplain mapping is not of sufficient resolution to consider effects of structural flood mitigation (e.g., dikes), and the mapping is limited to watersheds with at least 10 km^2 watershed area; it is intended as a screening tool to estimate hazard exposure and inform decisions for more detailed floodplain mapping.

The power law can be expected to hold within the channel, but not necessarily once the river floods beyond the channel. The power law assumption holds for relatively simple cross section geometries, not for compound ones where there is a channel and a floodplain (Ferguson, 1986). As such, the approach can overestimate the flood depth and the potential flood extent.

Watercourses with less than 10 km^2 watershed areas are not included in the hazard exposure analysis (VanDine, 1996). Such small watersheds may be additionally subject to steep creek hazards (e.g. debris floods and debris flows). In practice, this threshold is not absolute and can be refined using additional watershed characteristics (Church & Jakob, 2020). The current work delivers a flood hazard layer for baseline (current) conditions. A province-wide flood hazard layer with consideration of climate change remains a data gap at time of report issue[4].

A-6 COASTAL FLOODS

A-6.1 Hazard Definition

Coastal flood hazard is defined for exposure analysis as areas with potential coastal flood inundation for a 200-year flood event (0.5% AEP) under current conditions (2020) and with climate change (2100).

A-6.2 Data Inputs

BGC developed a Tier 1 coastal flood inundation layer along BC's coastline using terrain and oceanic data that includes a combination of storm surge, mean higher high water (MHHW) and sea level rise (SLR) data for current (2020) and climate change conditions (2100) (Table A-6-1).

[4] BGC is currently retained by Fortis Electric to prepare Tier 1 flood hazard mapping for BC that considers climate change.

Table A-6-1 Summary of key data inputs.

Data Type	Description	Reference[1,2]
Storm Surge	Storm surge data were provided by National Research Council (NRC) for current (2020) and projected climate change conditions (2100). The 99th percentile of daily maximum storm surges were estimated for the period of 2000 to 2020 to represent baseline storm surge conditions. Projected changes in daily maximum storm surges were estimated for the period of 2080 to 2099 using the results of a model ensemble (Multi-Model Maximum) for Representative Concentration Pathway (RCP) 8.5 scenario at the end of century.	**Cousineau and Murphy (2022)**
Mean Higher High Water	Mean higher high water (MHHW) data were provided by NRC (Julien Cousineau, pers. comm. April 26, 2024). Characteristic tidal surfaces were computed based on a 1-year TELEMAC-2D simulation spanning the entire year of 2000 with TPXO astronomical tidal forcing only.	**Cousineau and Murphy (2022)**
Sea Level Rise	Relative sea level rise (SLR) data were provided by NRC (Julien Cousineau, pers. comm. April 26, 2024) based on James et al. (2014) for current (2020) and projected climate change conditions (2100). SLR projections were based on RCP8.5 scenario at the end of century.	**James et al. (2014)**
Terrain	The DeltaDTM dataset has global coverage, at 30 m resolution in Canada, with a vertical mean absolute error of 0.45 m. The DeltaDTM uses lidar data to correct the elevation bias in the global Copernicus DEM.	**Pronk et al. (2024)**

Note:

1. Oceanic data received from NRC is available in .csv format: https://s3.modolo.ca/nrc/ocre/public/prod/tara/pacific/data/post/bcengineering/sea_mhhw_surve.csv

A-6.3 Hazard Layer Development

BGC used a topographic surface difference analysis approach to generate an interpolated coastal flood inundation layer for the following two scenarios based on a combination of data summarized in Table A-6-1:

- **Current Condition (2020):** SLR (2020) + MHHW + Storm Surge (Hindcast, 99th Percentile, 2000 to 2020)
- **Climate Change Condition (2100):** SLR (2100) + MHHW + Storm Surge (Multi-model Maximum, 99th Percentile, 2080 to 2099).

Additional geospatial work was required to convert the oceanic data (.csv format) received in Mean Sea Level (MSL) to a vertical datum (CGVD2013). BGC used a Continuous Vertical Datum surface received from the Canadian Hydrographic Service (CHS) to convert the oceanic data in Table A-6-1 from MSL to a vertical datum for the BC coastline. A raster dataset was then created to represent the combined data for each scenario by applying a 9-by-9 cell moving window that calculates the median value for raster cells that do not contain data. The estimated flood elevations were projected further inland by repeatedly applying the moving window until the potential area affected by coastal flooding is populated with flood elevations.

The extent of flooding was then estimated by calculating the topographic difference between the flood elevation raster and the digital terrain model used to represent the BC coastline

(DeltaDTM, published by Pronk et al., 2024) for each scenario (i.e., current and climate change conditions).

A-6.4 Hazard Exposure Analysis Logic

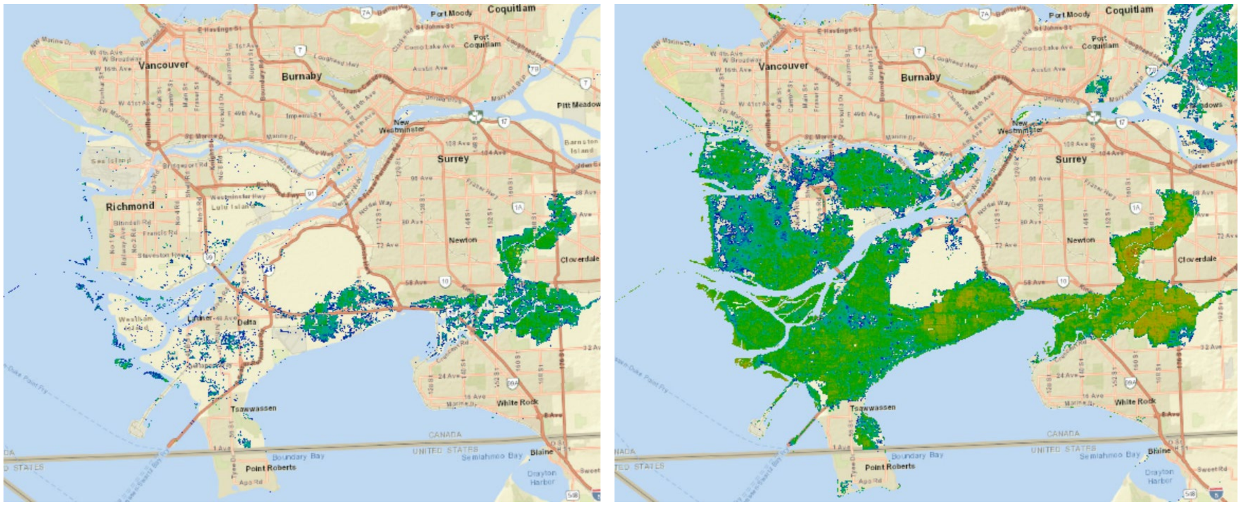
The hazard exposure analysis methodology was applied for coastal flooding as described in Section A-2 for all assets.

A-6.5 Gaps and Limitations

Gaps and limitations are described in Appendix B. BGC highlights the following uncertainties:

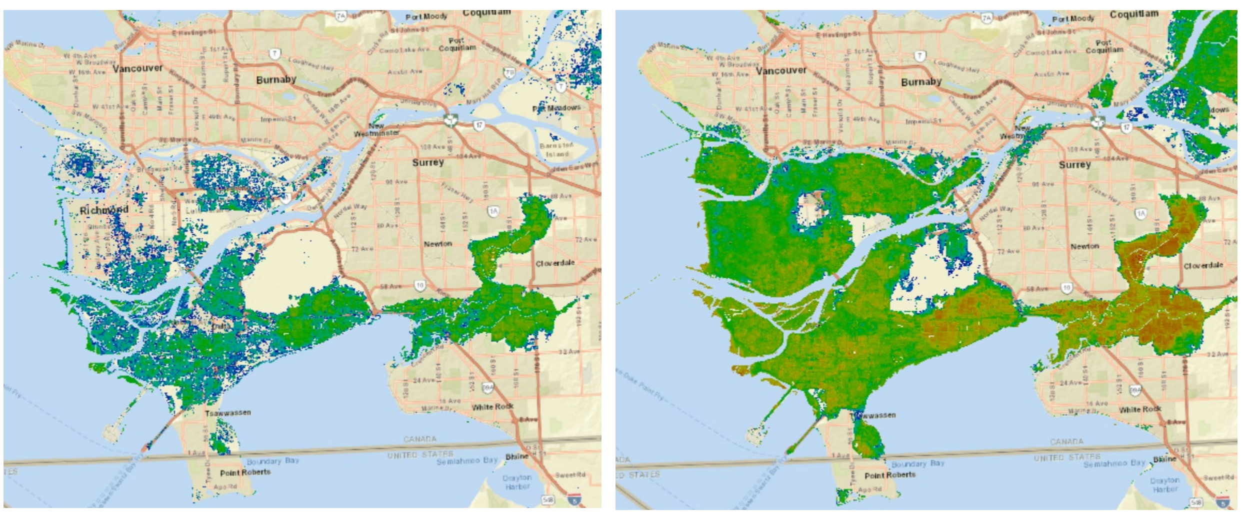
- Oceanic data used in the analysis was converted from MSL and interpolated between data points. The process of conversion and interpolation adds uncertainty in the flood layer.
- Oceanic data projections for storm surge and SLR were limited to the RCP8.5 scenario, which is representative of higher greenhouse gas emissions. SLR estimates include a predicted 1 m rise in sea levels at the end of century (2100) which may be revised with additional climate modelling.
- Coastal inundation extents do not consider effects of structural flood mitigation (e.g., dikes) or effects of high flows in coastal streams; it is intended as a screening tool to estimate hazard exposure and inform decisions for more detailed coastal mapping. Coastal inundation extents in low-gradient areas such as river deltas will also be sensitive to the vertical mean absolute error of 0.45 m of the DeltaDTM.
- Coastal flood inundation extents are greater with the inclusion of MHHW in the scenarios than without MHHW, as shown in Figure A-6-1 and Figure A-6-2 for an area of the Lower Mainland. A comparison to a coastal risk screening-tool for the Lower Mainland[5] showed similar inundation extents for the 2100 scenario (Figure A-6-2b, Figure A-6-3). As a result, MHHW heights were included in the scenarios and carried through the hazard exposure analysis to capture a 200-year flood (0.5% AEP) or greater event at a screening-level. BGC notes that the DeltaDTM does not have sufficient resolution to capture structural mitigation (e.g., dikes). As such, the results do not consider the effects of structural mitigation on reducing wave impacts (Figure A-6-1b and Figure A-6-2b). The coastal inundation layer also does not consider the potential influence of high flow conditions in streams adjacent to the coast on coastal flooding.

[5] https://coastal.climatecentral.org/map/11/-123.2335/49.2299/?theme=sea_level_rise&map_type=year&basemap=roadmap&contiguous=true&elevation_model=best_available&forecast_year=2100&pathway=ssp3rcp70&percentile=p50&refresh=true&return_level=return_level_1&rl_model=tebaldi_2012&slr_model=ipcc_2021_med



(a) (b)

Figure A-6-1 Example of coastal flood inundation extents (a) without Mean Higher High Water and (b) with Mean Higher High Water for the current condition (2020) scenario within the Lower Mainland. The example shown in (b) was carried through provincial hazard exposure analysis.



(a) (b)

Figure A-6-2 Example of coastal flood inundation extents (a) without Mean Higher High Water and (b) with Mean Higher High Water for the climate change condition (2100) scenario within the Lower Mainland. The example shown in (b) was carried through provincial hazard exposure analysis.

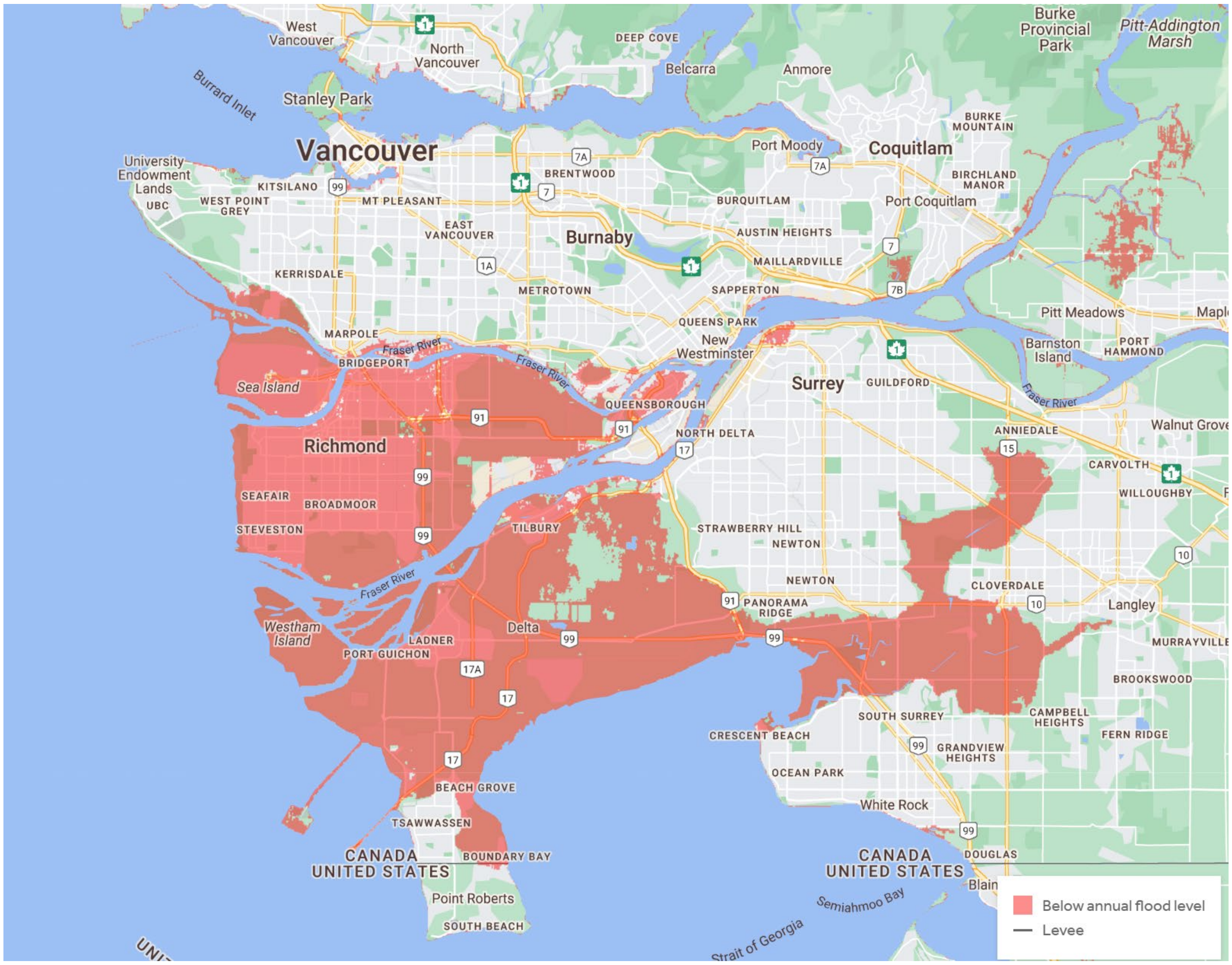


Figure A-6-3 Example of coastal flood inundation screening-level extents for the Lower Mainland for 2100 from Climate Central[6].

A-7 EXTREME HEAT

A-7.1 Hazard Definition

Extreme heat hazards refer to unusually hot temperatures and/or high humidex compared to the regional average seasonal air temperature. As a relative measure, the definition of "extreme" varies regionally because of physiographic conditions influencing temperature (ECCC, 2023).

Temperature thresholds for extreme heat warnings[7] have been established by ECCC in coordination with provincial/territorial health authorities. For BC, the criteria for extreme heat warnings are defined regionally using 1) Daytime Maximum Temperature and Overnight

[6] https://coastal.climatecentral.org/map/11/-123.2335/49.2299/?theme=sea_level_rise&map_type=year&basemap=roadmap&contiguous=true&elevation_model=best_available&forecast_year=2100&pathway=ssp3rcp70&percentile=p50&refresh=true&return_level=return_level_1&rl_model=tebaldi_2012&slr_model=ipcc_2021_med

[7] Heat warning criteria must be met for 2 days.

Minimum Temperature, or 2) Daytime Maximum Humidex. These regional thresholds form the basis of the British Columbia Heat Alert and Response System (BC HARS).

An extreme heat event is defined as a 3-day heatwave of comparable magnitude to the BC HARS.

A-7.1.1 Extreme Heat - Baseline

As a baseline estimate, “extreme heat” is defined as areas where the frequency of the 3-day average daily mean temperature exceeds the 50-year event over the historical period (1971-2000).

A-7.1.2 Extreme Heat – Climate Change

“Extreme heat”, with consideration of climate change, is defined as areas where the frequency of the 3-day average daily mean temperature exceeds the 50-year event over the future period (2041 to 2070). A single emission scenario was assumed based on Shared Socioeconomic Pathway (SSP) 5-8.5.

A-7.2 Data Inputs

BGC relied on data inputs analysed by Pacific Climate Impacts Consortium (PCIC) to complete all work (PCIC, 2024). As described by PCIC (2024), an ensemble of 9 statistically downscaled and bias-corrected Coupled Model Intercomparison Project (CMIP6) Global Circulation Model (GCM) simulations were used to describe changes in extreme temperature over British Columbia (CanDCS-M6). The GCM outputs were bias-corrected using gridded observational data (1950 to 2012) and downscaled to approximately 10 km using a multivariate technique. GCM outputs 2012 and earlier align well with the gridded observational data. GCM outputs 2013 and beyond consist of future projections.

PCIC conducted frequency analyses using the annual maxima 3-day average mean temperature over two periods of 30 years: baseline (1971 to 2000) and future (2041 to 2070). These time periods were assumed to be quasi-stationary for analysis. This frequency analysis was used to estimate the return period of the BC HARS thresholds historically and into the future.

A-7.3 Hazard Exposure Analysis Logic

The hazard exposure analysis methodology was applied to extreme heat as described in Section A-2 for all assets. Extreme heat exposure was only quantified for population assets. However, patterns of extreme heat illustrated by the hazard exposure maps may inform qualitative examination of extreme heat exposure across BC for a broader range of values than those directly considered.

A-7.4 Gaps and Limitations

Appendix B highlights gaps and limitations. In summary:

- It is difficult to know what emissions trajectory society will adopt into the future. One scenario is assumed: the SSP5-8.5 in the CMIP6 GCM projections, corresponding to a radiative forcing of 8.5 W/m^2 by the end of century.
- The reference period assumed is the 1950 to 2012 set based on the analysis conducted by PCIC in the development of the CanDCS-M6 dataset.
- One future period was assumed to calculate the change in extreme heat hazard probabilities from the reference period. While the impacts of climate change are not necessarily linear with time, evaluations of mid-century and late-century should capture most of this non-linear behaviour (C., Curry, pers. comm., January 1, 2024).

A-8 METEOROLOGICAL DROUGHT

A-8.1 Hazard Definition

Meterological drought hazards refers to abnormal, prolonged dry periods resulting in an imbalance in the water cycle (Tam et al., 2023). In BC, severe and frequent droughts typically occur in the interior valleys due to low precipitation (rainfall and snowmelt) and are accompanied by low streamflow. For this project, a metric for meterological drought was used based on the provincial scale. A meterological drought is characterised by the difference between precipitation (P) and potential evapotranspiration (PET).

A-8.2 Data Inputs

The Standardized Precipitation Evapotranspiration Index (SPEI) is a metric intended to characterise meterological drought and was used to conduct the drought hazard assessment. SPEI is a relative measure of surface water surplus (for positive values) or deficit (negative SPEI values) with respect to hydroclimate of the reference period (Tam et al., 2023). This dataset was developed by researchers at ECCC at a grid cell resolution of approximately 100 km x 100 km. The data was provided to BGC in NetCDF format by Laura Van Vliet on March 3, 2024. Refer to the Tam et al., (2023) reference for additional information on the dataset.

A-8.3 Hazard Layer Development

A metric of trend, Kendall's Tau (Kendall, 1938), was calculated for each GCM time series available in each grid cell in BC to assess the direction and strength of a changing SPEI for the entire period of record. This provides an exploratory, high-level picture of change.

The frequency of the 12-month SPEI was calculated for the reference (1950 to 2014) and future (2041 to 2070) in each grid cell using standard frequency analysis methods. A Skew Normal distribution was fit to the data in each time window using the maximum likelihood estimator (MLE), from which the 50-year SPEI were calculated. A binary mask for SPEI values of <-2 was applied to indicate a threshold for extreme drought events.

Figure A-8-1 shows extents of the 50-year SPEI across BC (red grid cells) for the reference period (1950 to 2014) (a) and future period (2041-2070) (b). For the reference period, the red and white pattern is an artifact of sampling variability combined with a slight difference between the actual return period of an "extreme" (SPEI<-2) drought (44-year drought) and a 50-year event.

As a starting point for comparing relative change in future, the reference period (a) was not required in the exposure analysis. The historical information is implicit in the standardized nature of the SPEI. The future period (b) shows that the distribution of SPEI is shifting towards drier condition (more negative SPEI) in areas highlighted by the red cells such that extreme drought (SPEI of -2) is becoming more frequent in those areas. These areas are exposed by a worse 50-year drought by 2041 to 2070 compared to the reference period (1950 to 2014).

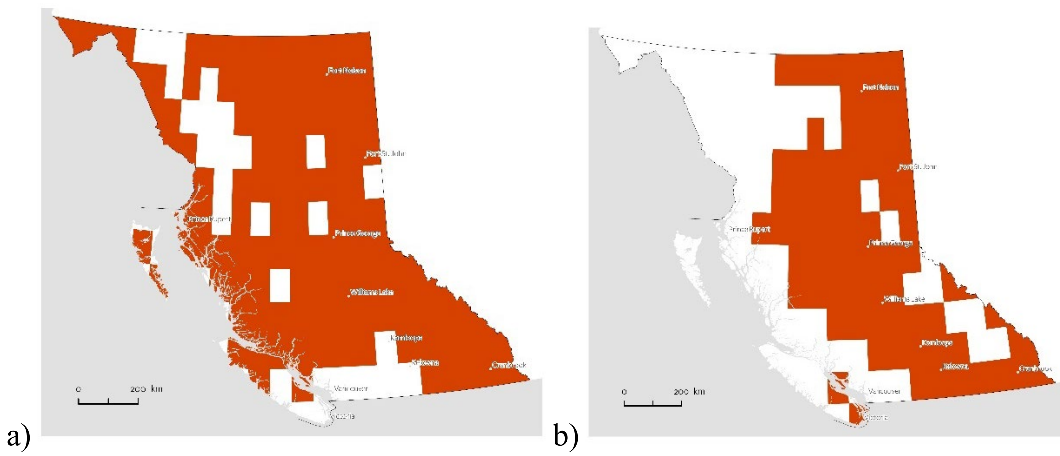


Figure A-8-1 Extreme (50-year) SPEI for the reference period (1950 to 2014) (a) and future period (2041-2070) (b). As noted above, the future image (right) shows areas projected to experience more drought.

A-8.4 Hazard Exposure Analysis Logic

The hazard exposure analysis methodology was applied to drought as described in Section A-2 for populations and environmental assets. However, BGC notes the following important difference between the drought hazard layer and other hazard layers carried through exposure analysis:

- As a standardized measure of meterological drought, SPEI for the reference period do not show patterns of varying drought level across BC in absolute terms. They provide a reference for comparison to future conditions, and were not used in exposure analysis.
- The hazard exposure analysis focused entirely on the future period (2041 to 2070). The results identify areas of the province threatened by higher levels of extreme drought in future compared to that experienced in the past (1950 to 2014) (Figure A-8-2).

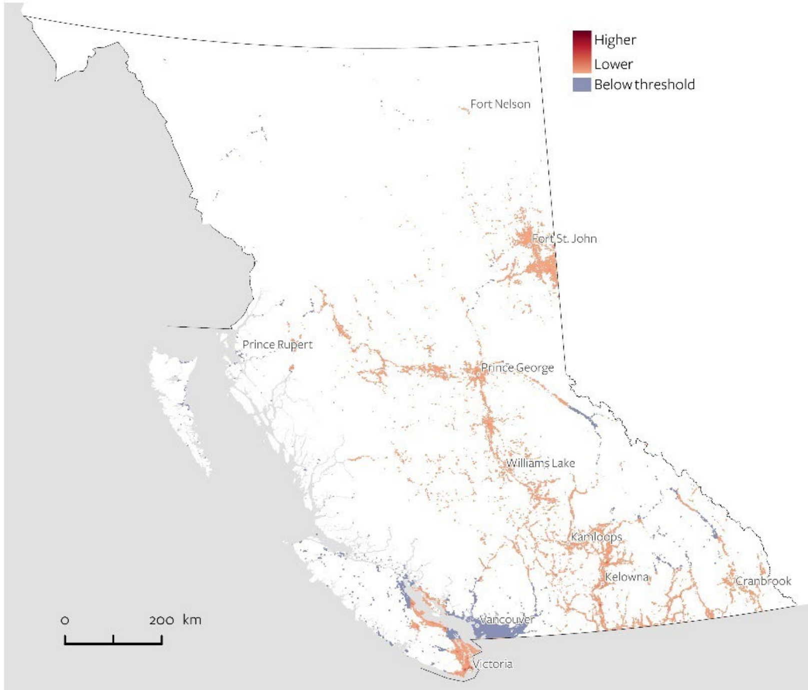


Figure A-8-2 Population densities threatened by a worse 50-year meterological drought by 2041-2070, compared to what they experienced in the same area historically (1950 to 2014).

A-8.5 Gaps and Limitations

Gaps and limitations are described in Appendix B. BGC highlights the following uncertainties:

- The SPEI is intended to be a standardized index showing change in drought relative to the 1950 to 2014 reference period (Tam et al., 2023). The SPEI is not intended to show future absolute changes from historical conditions in drought across BC. Instead, the SPEI in each grid cell is relative to a level playing field (reference period) showing the direction of change in a future 50-year drought.
- The SPEI assumes a normal distribution with a mean of zero and a standard deviation of 1 based on the 1950 to 2014 reference period. The normal distribution assumption implies that an SPEI of -2 is equivalent to a 44-year event. The implication of rounding to the 50-year event for ease of communication of an extreme event is such that any amount of drying (including no drying) or slight wetting will be captured on the map. In this way, this map is a conservative picture of the drought hazard in the future.
- The resolution of input datasets and outputs is 100 km. As such, the representation of drought extents for the purpose of hazard exposure analysis may not necessarily meaningfully capture valued assets at the boundary of hazard extents. As with all hazard types, it is important to convey that areas falling below the threshold for drought exposure as shown on the maps may still be subject to drought under different threshold criteria.

- It is difficult to know what emissions trajectory society will adopt into the future. One scenario is assumed: the SSP5-8.5 in CMIP6 GCM projections, corresponding to a radiative forcing of 8.5 W/m^2 by the end of century. All 26 CMIP6 GCMs in this scenario were analysed.
- One future time period defined by 30 years (2050; 2041 to 2070) was assumed with the results relative to the historical reference period (1950 to 2014). While the impacts of climate change are not necessarily linear with time, evaluations of mid-century should capture most of this non-linear behaviour (C., Curry, pers. comm., January 1, 2023).

A-9 WILDFIRES

A-9.1 Hazard Definition

Wildfire hazards refer to uncontrolled burning of wildland vegetation. Wildfire hazard potential extends province-wide, including both undeveloped areas and vegetated areas within urban development areas, and across both private and public land. See the note in Section A-9.5 regarding exclusion of private land from available wildfire hazard threat mapping.

A-9.2 Data Inputs

The “Provincial Strategic Threat Analysis” (PSTA) geospatial dataset (BC Wildfire Service [BCWS], 2021) was used as the input for the wildfire hazard component of the hazard exposure analysis. This dataset represents an approximate relative wildfire threat assessment at the provincial scale for all wildland in BC, in raster format at 90 m resolution.

A-9.3 Hazard Layer Development

As described by BCWS (2021), primary data inputs to wildfire hazard exposure analysis include the following:

- BC Forest Vegetation Inventory
- Historical Wildfire Points greater than 4 ha
- Provincial Digital Elevation Model (DEM)
- BC Fuels Layer
- 90th Percentile Fire Weather.

Mapping excludes private land and extends into a wildland urban interface area. This area is defined based on 2 km buffer from areas with a structure density greater than 6 structures/km, or a 1 k m buffer in areas with a structure density of less than 6 structures/km.

BCWS (2021) reports that this structure density was “primarily derived from Address BC and information from the Integrated Cadastral Information Society, and was supplemented with TRIM and other local data.” Results are reported as categorical fire threat ratings, ranging from 1 (Low) to 10 (Extreme).

For the purpose of hazard exposure analysis and with input from the DCRRA Wildfire Working Group, wildfire hazard exposure was defined as any areas with a fire threat rating of 6 (Moderate) or higher.

A-9.4 Hazard Exposure Analysis Logic

The hazard exposure analysis methodology, as described in Section A-2, was applied for All PSTA data where hazard threat was Moderate or higher.

A-9.5 Gaps and Limitations

Appendix B summarizes gaps and limitations for all data. BGC highlights that BCWS (2021) is intended to cover the forested land base, and the majority of developed land is excluded from the analysis including greenspaces within developed areas that may also be susceptible to wildfire hazard.

Specifically, the BCWS (2021) mapping excludes private land and extends only into a wildland urban interface area (buffer). The buffer surrounds areas “primarily derived from Address BC and information from the Integrated Cadastral Information Society, [which were] supplemented with TRIM and other local data” and will also contain uncertainty. BCWS (2021) also does not take into consideration factors that may influence fire activity, such as individual structure components (roofing and sidings) and fences.

Because most developed land exists in areas excluded from analysis, wildfire hazard threat mapping is only representative of mapped areas and will underestimate wildfire hazard exposure to developed lands in most areas of BC.

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APPENDIX B
GAPS AND LIMITATIONS

Type	Area	Description	Implications	Considerations to Resolve
Valued Assets	Summary - Content	Gaps exist in the valued data model in terms of location, attributes, and data formats. Specifically, the layers are based on the best information available at the time of study but are not complete. Local and Indigenous knowledge of valued assets represents a key gap outside the scope of the provincial scale study.	Potential gaps in information leading to underestimation of hazard threat (e.g. missing assets), or overestimation of hazard threat (e.g., where assets not located within hazard extents are still captured due to coarse resolution of datasets).	Consider avenues to refine and support programs that provide regularly maintained and disseminated asset data models in a format amenable to hazard and risk assessment (e.g. ICI Society)
	Summary - ICI Society Data	Much data about built environment valued assets in BC, including utility networks, is maintained by the Integrated Cadastral Information (ICI) Society. These data represent a valuable source of built environment data for disaster hazard threat and risk assessment. However, the data model was not originally organized for such use and requires substantial re-work (e.g. grouping, categorizing) to prepare for hazard threat analysis.	Increased effort and cost to prepare built environment data layers for hazard threat and risk analyses. This increase in effort increases multifold by each risk assessment completed that relies on these data.	In collaboration with ICI Society, review and consider updates to data organization and format to facilitate hazard threat, vulnerability and risk analysis.
	Population	Census breakdown of population totals in NRCAN (2022) is based on 2016 Census data. BGC obtained a version of the NRCAN (2022) layer updated to include 2021 Census population, but the update was limited to population totals (not demographic breakdowns or social vulnerability indices). Census data may also under-represent populations with lower rates of response to census data requests, and for occupied areas not represented by Census data (e.g. non-residential)	Other than total population, changes in population and characteristics since the 2016 Census are not represented in the results. A proposal exists to create an updated vulnerability dataset targeting BC based on established best practices and accounting for future growth projections across the province but was not available at the time of the provincial assessment	Create an updated vulnerability dataset targeting BC, based on established best practices and accounting for future growth projections across the province. Consider approaches that facilitate future maintenance and updates from an information management perspective.
	Built Forms (First Nations Reserves)	Built forms (parcel improvements) are not represented by BC Assessment (BCA) data on reserve lands. NRCAN physical exposure layer provides estimates of building replacement value aggregated at settlement area level of detail, but at lower resolution and without attribution amenable to vulnerability analysis. No data source for actively maintained built form data on FN reserves has been identified in a format amenable to regional scale, parcel or building resolution, hazard threat, vulnerability or risk analysis. In a 2022 assessment outside of the DCRRA project, BGC completed select quality control of NRCAN Built Form values for First Nation reserve areas in Squamish-Lillooet Regional District, based on comparison of the number of visible building footprints to the number of buildings NRCan's data set reports for an area. In summary, NRCan's estimated number of buildings generally matched observations, but BGC did find several cases where structures were undercounted by up to 30%.	High uncertainty and likely underestimation of built form values on First Nations reserves, with subsequent implication for underestimation of loss due to hazards.	Review programs for the maintenance and distribution of built form geospatial data that can be efficiently accessed at province-wide scale (e.g. do not fragment data access between reserve areas).
	Built Forms (Data availability)	BC Assessment data joined to cadastral fabric at folio level of detail greatly facilitated hazard threat analysis completed for the DCRRA, compared to the standard (Excel or XML format) BCA reports typically issued by BC Assessment to local governments, which require a complex data join to ParcelFabricBC data.	Substantial benefits of spatial BCA data used for the DCRRA are not commonly known about or made available to local governments undertaking work under other programs (e.g. Disaster Risk Reduction - Climate Adaptation).	Consider actions to facilitate broader provision of BC Assessment data in spatial format (joined to the cadastral fabric) to local governments. Such provision would greatly reduce the cost of compiling built form data for risk assessments for local governments.
	Built Forms (Data format)	BC Assessment data joined to cadastral fabric contains polygons at folio level of detail. For example, a condominium tower with many units (folios) will have many polygons stacked on top of each other. These were flattened and assigned a primary actual use and total value for provincial scale analysis.	More detailed analysis may require folio level of detail, such as to distinguish a retail ground floor from residential upper stories of a building for flood loss estimation.	Preserve folio level of detail of spatial analysis for the completion of regional-local stages of assessment, where required to apply appropriate vulnerability criteria.
	Built Forms (Valuation)	Hazard threat analysis uses assessed built form values, which may differ from replacement costs.	Potential underestimation of disaster recovery costs where replacement costs exceed depreciated assessed built form values.	Maintain the use of a regularly updated dataset (BC Assessment); if replacement values are desired, consider BCA data fields as a data source for provincial scale estimation workflows.
	Built Forms (Building Footprints)	Provincial hazard threat analysis for Built Forms was completed at parcel scale, using available BC Assessment attributes. The location of buildings within a parcel is not captured at the scale of assessment.	While parcel scale assessment is considered reasonable given the scale of study and available resolution of hazard layer inputs, varying hazard levels within a parcel are not captured at the scale of assessment. While considered reasonable for province-wide hazard threat analysis, the level of detail of built form characterization is not necessarily sufficient to analyse vulnerability to loss, for a given hazard type, and the characteristics needed to estimate vulnerability may differ between hazard types (e.g., compare extreme heat to earthquakes and floods).	Tier 2+ assessments at regional-local scale may require building scale resolution to assess hazard threat (or subsequent steps of risk assessment) at a level of detail required for local decision making. Consider updates (e.g. at regional phase of DCRRA) to spatial analysis workflows to incorporate building footprints into provincial scale hazard exposure analysis, even if results continue to be reported at parcel scale. Consider opportunities to engage with the building assessment process to collect and share additional information relevant for disaster risk assessment, using a process that is already regularly maintained and updated.
	Mining assets	Hazard threat analysis scope did not include consideration of mine assets (e.g. mine site and waste management facilities)	Hazard threat to the mining sector, including critical minerals, is not considered in the DCRRA.	Consider adding a provincial inventory of mine assets to the geospatial hazard threat analysis workflows.
	Critical Facilities	With the exception of additional, manually compiled locations within the Squamish-Lillooet Regional District, Thompson-Nicola Regional District and Regional District of Central Kootenay, critical facilities were identified using a rules-based approach (BC Assessment Actual Use Descriptions), spatially represented by a point at the centroid of a given parcel. Given the source of data, facilities critical for reasons related to cultural importance are not included.	Local communities may have facilities critical for function in an emergency that are not identified at the scale of assessment, or that would not be identifiable without local knowledge (e.g. a parking lot containing emergency response resources). Locations at parcel centroid do not reflect the actual building location and may be highly uncertain within large parcels. Because BC Assessment data does not extend to First Nations reserve, on-reserve critical facility types and locations remain an unresolved gap.	Engage with First Nations and local governments to refine province-wide inventory of critical facilities. Consider approaches that facilitate future maintenance and updates from an information management perspective. Map critical facilities to actual b building locations. Additionally incorporate linear critical facilities (e.g. critical evacuation routes, including forestry roads) and facilities important from a cultural perspective.
	Businesses	Total Annual Revenue data is based on uncertain categorical estimates within commercial data sources. Revenue cited for a given business location is not necessarily related to business activities at that location.	Uncertainly related to business disruption given hazard impact.	
	Environmental Values	Environmental values considered in the assessment (Old Growth Management Areas, Parks and Protected Areas, Fisheries Information Summary System (FISS) locations, and Species and Ecosystems at Risk) have very different vulnerabilities to hazard compared to the built environment.	Hazard thresholds selected for spatial hazard threat analysis are generalized for provincial scale application. While spatial relations between hazards and ecosystems will inform subsequent steps of regional assessment, the term "threat" should be used with caution (is not comparable to built environment assets).	Consider additional hazard scenarios and threshold criteria in subsequent stages of assessment tailored more specifically to vulnerabilities within natural ecosystems.
	Linear facilities (road, rail, utilities)	Analysing credible threat to linear facilities is highly location-specific and may include mechanisms of damage not well represented by spatial intersection of hazard extent with an asset centerline.	Over-estimation of hazard threat for some hazard types that include a span (e.g. communication or electrical line) between tower locations located to either side of a hazard extent (e.g. flood area). Uncertain estimate of hazard threat for assets requiring distinct approaches for threat analysis (e.g. buried pipelines).	Many linear infrastructure operators in BC operate long-term asset and risk management programs maintained by consultants. Consider engagement with infrastructure operators and their consultants to identify opportunities to share resources, knowledge and tools, to advance shared risk management objectives.
	Municipal assets	Gaps exist for utilities and other asset data that is exclusively managed at a municipal level and not present within provincially compiled sources (ICI Society).	Underestimation of hazard threat for municipally managed assets not present within the database.	Consider municipally managed asset data sources for subsequent steps of regional-local scale assessment

Type	Area	Description	Implications	Considerations to Resolve
Hazards	Summary	Limitations to hazard data exist at each step of preparing data layers including inputs, workflows, and outputs. Separate documentation should be read for gaps and limitations associated with third party hazard data sources. For the purpose of hazard threat analysis, all hazard layers are based on a single probability of exceedance and hazard intensity threshold. Hazard exceedance probabilities differ between hazard types by up to one order of magnitude. Choosing a different hazard exceedance probability and intensity threshold would lead to different results.	The definition of "at threat" is contingent on the definition of the hazard area. Areas not identified as at threat may be at threat from lower probability, larger hazard events, or at a lower hazard intensity threshold.	Hazard layer criteria (probability of exceedance and intensity threshold) should be referenced when describing assets at threat. Considering additional hazard scenarios and intensity criteria may be warranted at subsequent regional-local phases of assessment.
	Seismic (ground shaking)	As noted by the DCRRA Earthquake Working Group, PGA is not a good metric to estimate damage, and that the correlation of damage to many types of structures with PGA is poor. Spectral acceleration was not included as a metric for provincial scale assessment. Additional limitations may be noted in 3rd party data sources used in analysis.	Under- or overestimation of credible threat to valued assets.	Consider additional metrics (spectral accelerations), additional scenarios, and more detailed mapping (e.g., seismic microzonation mapping) in subsequent stages of assessment.
	Seismic (co-seismic landslides)	Current information applied to screen for co-seismic hazard potential is based on simplified criteria and is not intended to represent hazard susceptibility or hazard level for more detailed assessment. Co-seismic landslide susceptibility mapping (or even landslide susceptibility mapping) does not exist province-wide at a level of detail that can support regional-local scale assessment. Additional limitations may be noted in 3rd party data sources used in analysis.	Under- or overestimation of credible co-seismic landslide threat to valued assets.	Consider resources to prepare province-wide, Tier 1 landslide and co-seismic landslide susceptibility maps.
	Seismic (liquefaction)	Current information applied to screen for co-seismic liquefaction potential is based on simplified criteria and is not intended to represent hazard susceptibility or hazard level for more detailed assessment. Co-seismic liquefaction mapping does not exist province-wide at a level of detail that can support regional-local scale assessment. Additional limitations may be noted in 3rd party data sources used in analysis.	Under- or overestimation of credible co-seismic landslide threat to valued assets.	Consider resources to prepare Tier 1 co-seismic liquefaction maps with sufficient coverage for areas targeted at regional assessment..
	Riverine Flooding	Section 8.0 of Tier 1 flood hazard mapping prepared by BGC (April 19, 2024) and used for hazard threat analysis describes limitations that should be read with this report. These include but are not limited to the range of flood hazard types assessed, the resolution and quality of input data, and simplifying assumptions in the analysis. Tier 1 floodplain mapping is not of sufficient resolution to consider effects of structural flood mitigation (e.g., dikes). Mapping is limited to watersheds with at least 10 km2 drainage area.	Under- or overestimation of credible riverine flood threat to valued assets. Watercourses less than 10 km2 are not included, and may be subject to steep creek hazards (e.g. debris floods and debris flows) not included in hazard threat analysis.	With appropriate subject matter expertise, consider refining hazard threat analysis methods developed by this project with higher resolution flood hazard mapping, including additional scenarios and consideration of additional parameters of risk (vulnerability). BGC is currently retained by Fortis Electric to update province-wide Tier 1 floodplain mapping to consider climate change, and classify watercourses subject to steep creek process types on small drainages. Consider updates to hazard threat analysis following delivery of the updated hazard mapping.
	Coastal Flooding	In gentle areas such as deltas, the outer boundary of flooded extents may show grid cells disconnected from neigbouring waterways. Coastal inundation extents in low-gradient areas such as river deltas will also be sensitive to the vertical mean absolute error of 0.45 m of the 30 m DeltaDTM. Oceanic data used in the analysis was converted from MSL and interpolated between data points, and the process of conversion and interpolation adds uncertainty in the flood layer. Oceanic data projections for storm surge and SLR were limited to the RCP8.5 scenario, which is representative of higher greenhouse gas emissions. SLR estimates include a predicted 1 m rise in sea levels at the end of century (2100) which may be revised with additional climate modelling.	Over-estimation of flood inundation where detailed analysis identifies modelling artefacts, or under-estimation of flood inundation where detailed analysis would connects isolated grid cells into contiguous extents. Over- or under-estimation of flood inundation due to uncertainty in the interpolation of conversion and interpolation of elevation data points. Over- or underestimation of flood inundation related to uncertainties in the assumption of a RCP8.5 climate scenario.	Where data exists, update modeling to incorporate high resolution topography (e.g. lidar) and surveyed hydraulic controls (e.g. flood protection structures). Update the analysis when needed to reflect results of climate model updates or consideration of different climate change scenarios.
	Wildfire	The BCWS (2019) mapping excludes private land and extends only into a wildland urban interface area (buffer). It is intended to cover the forested land base, and the majority of developed land is excluded from the analysis including greenspaces within developed areas that may also be susceptible to wildfire hazard. It also does not take into consideration factors that may influence fire activity, such as individual structure components (roofing and sidings) and fences.	Because the majority of developed land exists in areas excluded from analysis, wildfire hazard threat mapping will underestimate wildfire hazard threat to developed lands in most areas of BC.	Consider updated wildfire hazard mapping data sources that do extend to private lands.
	Extreme Heat	Hazard thresholds defined for extreme heat reflect ECCC heat warning regions and are not applicable for hazard threat analysis to valued assets other than population. Hazard threat to other assets (e.g. extreme heat threat to transportation infrastructure) was not included in the scope of analysis.	Gaps in hazard threat understanding for the range of assets threatened by extreme heat.	Update hazard threat analysis to include additional heat scenarios applicable to analysis hazard threat to the full range of potentially vulnerable asset types.
	Climatic Drought	See Appendix A for additional discussion of limitations. The resolution of input data and analysis outputs for drought hazard layers are coarse (100 km grid scale) and apply simplified criteria. Additional areas of BC may be subject to drought that are not captured by currently available data or selected thresholds.	Under-estimation of drought hazard in areas not currently captured by available resolution data or defined thresholds. Spatial analysis may mis-identify hazard threat due to the coarse grid cell resolution (e.g. where square boundaries of large grid cells do not capture the actual pattern of drought extent).	Consider additional range of scenarios at different threshold levels to increase spatial granularity of drought. The SPEI is a standardized index relative to the 1950 to 2005 period. Consider a non-standardised index to characterise change across a range of historical periods.
Spatial Analysis	Spatial intersection	Provincial scale geospatial hazard threat analysis entirely relies on the spatial intersection of hazards with assets to identify threat.	Additional hazard threat may exist where assets do not spatially intersect hazard areas as defined for provincial scale assessment. For example, a road adjacent (but not intersecting) a flood hazard area may still be subject to erosional impact, or an asset in the runout zone of a co-seismic landslide may be located outside the mapped hazard area.	Additional methods for hazard threat, vulnerability and risk assessment will be required at regional-local scale assessments that are specific to hazard type.
	Scenarios	Across all hazards considered for hazard threat analysis, the analysis is based on a single combination of hazard probability and threshold criteria to indicate threat. All hazards considered follow a frequency-magnitude relationship with an unlimited number other scenarios besides those considered in this study. Assets not identified as "at threat" by spatial analysis should be interpreted as falling outside the criteria used to define hazard, limited by the resolution and quality of available data; the possibility of hazard threat based on other criteria or input data cannot be ruled out. All inputs are a snapshot in time, and changed conditions for either valued assets or hazard conditions may result in hazard threat not identified in this study.	Potential unidentified threats to valued assets.	Leverage developed workflows to incorporate higher resolution hazard and asset datasets (e.g., at regional-local scale), additional scenarios, and updates as new information becomes available.
Climate Change	All hazards	Climate-adjusted hazard layers were prepared only for climate hazards (heat and drought). Second-order effects of climate change were not considered for other hazard types at provincial phase of assessment.	Potential underestimation of hazard threat with climate change for riverine flood, wildfire, and co-seismic hazard types.	As data permits, consider climate change effects on remaining hazard types at regional-local scales of assessment.

APPENDIX C
DATA SCHEMA AND HAZARD EXPOSURE STATISTICS (PROVIDED UNDER SEPARATE COVER)

Provided to the Ministry of Emergency Management and Climate Readiness.

APPENDIX D
METADATA (PROVIDED UNDER SEPARATE COVER)

Provided to the Ministry of Emergency Management and Climate Readiness.

APPENDIX E
MAPS AND CHARTS (PROVIDED UNDER SEPARATE COVER)

Provided to the Ministry of Emergency Management and Climate Readiness.

APPENDIX F
SOFTWARE CODE
(PROVIDED UNDER SEPARATE COVER)

Provided to the Ministry of Emergency Management and Climate Readiness.

APPENDIX G
GEOSPATIAL DATA
(PROVIDED UNDER SEPARATE COVER WITH FILE NAMES AS NOTED IN APPENDIX D, METADATA)

Provided to the Ministry of Emergency Management
and Climate Readiness.

British Columbia Provincial Climate Overview: Annex

For the Provincial Risk Assessment

April 30, 2024; last revised February 27, 2025

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1. Introduction

1.1 Key concepts

In recent years, human-caused climate change has become a pressing reality. By the end of 2022, global mean surface temperature had risen by approximately 1.2 ^{o}C since the pre-industrial era (1850-1900; Forster et al., 2023), followed by the warmest year ever recorded on the planet: the 2023 annual global mean temperature reached 1.48 ^{o}C above pre-industrial (IPCC, 2023; Copernicus Climate Bulletin, 2023). Canada is warming at nearly twice the global rate (Lulham et al., 2023). While global climate change has occurred in the distant past due to natural processes such as changes in the Earth's orbit/tilt or volcanic activity, the pace of the current warming is far greater than anything in the paleoclimate record and has been unequivocally linked to the rise of anthropogenic greenhouse gas concentrations (IPCC, 2023).

Any overview of the climate, or climate change, must first recognize the distinction between climate and weather. An understanding of the relevant time scales is essential (Figure 1). Weather refers to the short-term conditions of the atmosphere at a specific location. Weather is highly variable, and can change from minute-to-minute, hour-to-hour, and day-to-day. Climate, on the other hand, is the statistics of weather in a specific location or region over a longer period of time – usually 30 years or more. The statistic could be a time-average, or standard deviation, or frequency of a certain type of event, each a summary over the lengthy period. Climate varies, just like weather, but on time scales from seasons to decades and longer. Two particular modes of natural climate variability that have noticeable effects in British Columbia (BC) are the El-Nino Southern Oscillation and Pacific Decadal Oscillation (Whitfield et al., 2010). Their influence has been found to be strongest in winter: for example, winters during La Niña tend to be cooler and wetter than average, while El Niño winters tend to be somewhat warmer and drier. Finally, the climate change that is now upon us has become evident only on the scale of decades, but its impacts may persist for centuries (Figure 1).

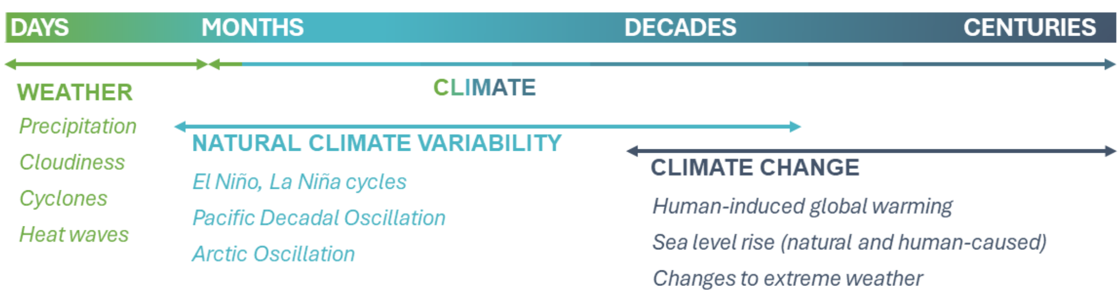

Figure 1. Schematic comparing the temporal characteristics weather, climate, and natural climate variability. Modified from ClimateData.ca Training Materials.

1.2 Brief overview of recent historical climate, globally and in BC

Figure 2 shows annual surface temperature change over the globe (1900-2023) and in BC (1948-2021) relative to the 1971-2000 historical mean (solid lines). We use 1971-2000 as a historical reference period to provide a baseline for comparison with future projections that also corresponds to the period of the most complete station data. In both cases, the linear trends indicate warming over the respective periods (dashed lines), with a much faster rate of warming in BC over the last 74 years. The year-to-year fluctuations in temperature seen in both time series are due to natural climate variability, which is much larger at the regional scale (BC) than it is on the global scale.

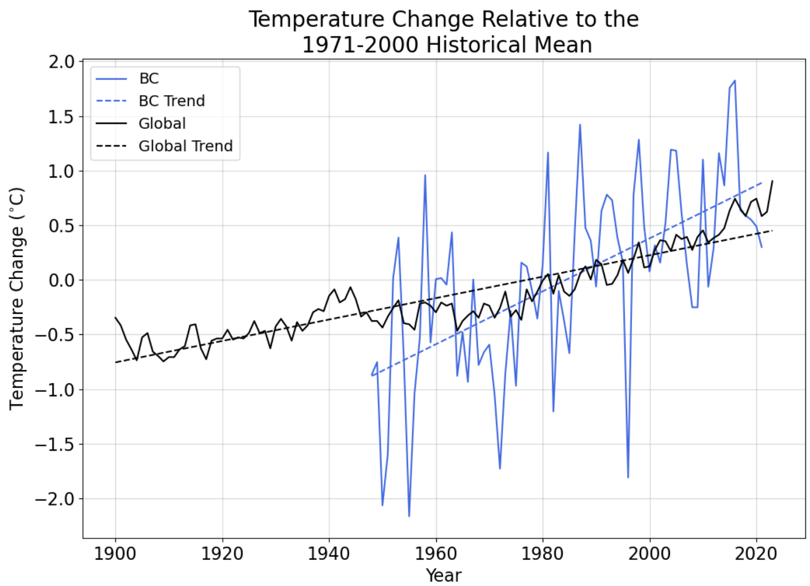

Figure 2. Annual surface temperature change globally (1900-2023; black curve) and in BC (1948-2021; blue curve) relative to the corresponding 1971-2000 mean temperature. The global time series is based on the Goddard Institute for Space Studies (GISTEMP) gridded station temperature product (NASA-GISS, 2024), while the BC series is derived from the Provincial Climate Dataset (PCDS) maintained at PCIC. Linear trends, both of which are statistically significant at the 5% level, are indicated by the dashed lines.

Similarly, Figure 3 shows annual total precipitation change over the globe and in BC relative to the 1971-2000 historical mean. Here, no significant long-term trend is evident in either time series. From this figure we observe that the natural variability of precipitation is much larger, relative to any long-term change, than for temperature.

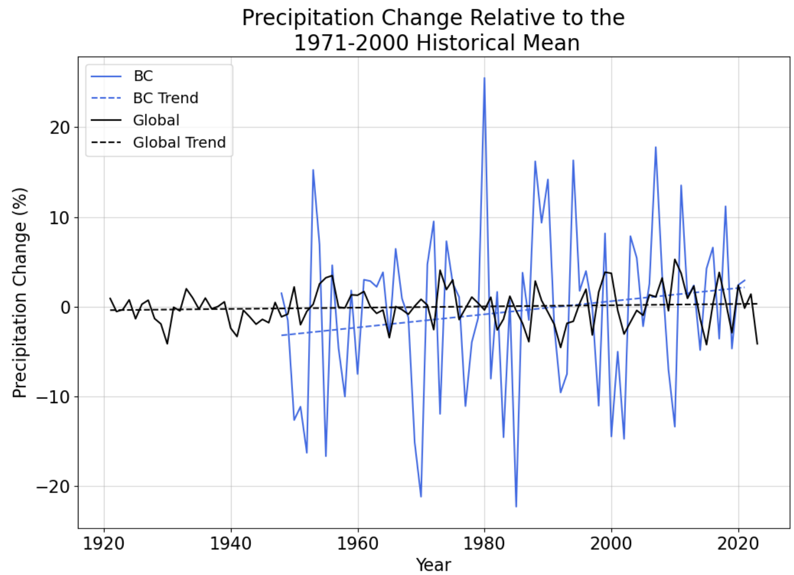

Figure 3. Same as in Figure 2 but for annual precipitation change, using global data from 1921-2023. In this case, the global time series is based on the Global Precipitation Climatology Centre (GPCC) gridded station precipitation product, while the BC series is derived from the PCDS. GPCC was accessed via the KNMI Climate Explorer (https://climexp.knmi.nl/).

1.3 Climate extremes

Climate is defined as the statistics of weather, and the average of a climate variable is just one such statistic. In reality, each variable has a distribution of values that describes its full behaviour over some period of interest. An illustration is provided in Figure 4 for temperature. Each of the three panels shows two curves: one for the "Previous (i.e. historical) climate" and one for the climate of a future period ("New climate"). The Previous climate curve is centered around the average temperature, which for temperature is also the most probable temperature. There is an equal probability in the Previous climate of warmer than average or cooler than average temperatures, as indicated by the corresponding area under the curve. The tails of the Previous distribution, representing extreme high and low temperatures, have low values of probability.

Fig. 4a shows an example where the average (or mean) temperature increases, but the width of the distribution (often measured by the variance or its square root, the standard deviation) does not change in the future climate. Fig. 4b gives an illustration of a situation where the average temperature doesn't change, but the variance increases. One would say that the weather has become more variable in the New climate. Here we expect to see both more record hot and more record cold temperatures. Fig. 4c gives an example with both the mean and the variance increasing. In this case, the shift of the entire distribution to higher temperature leads to much more frequent hot and near-record heat, but less cold weather than in the previous climate. As demonstrated by the vast body of climate change research, this is the case best supported by observations of the real climate system (IPCC, 2021).

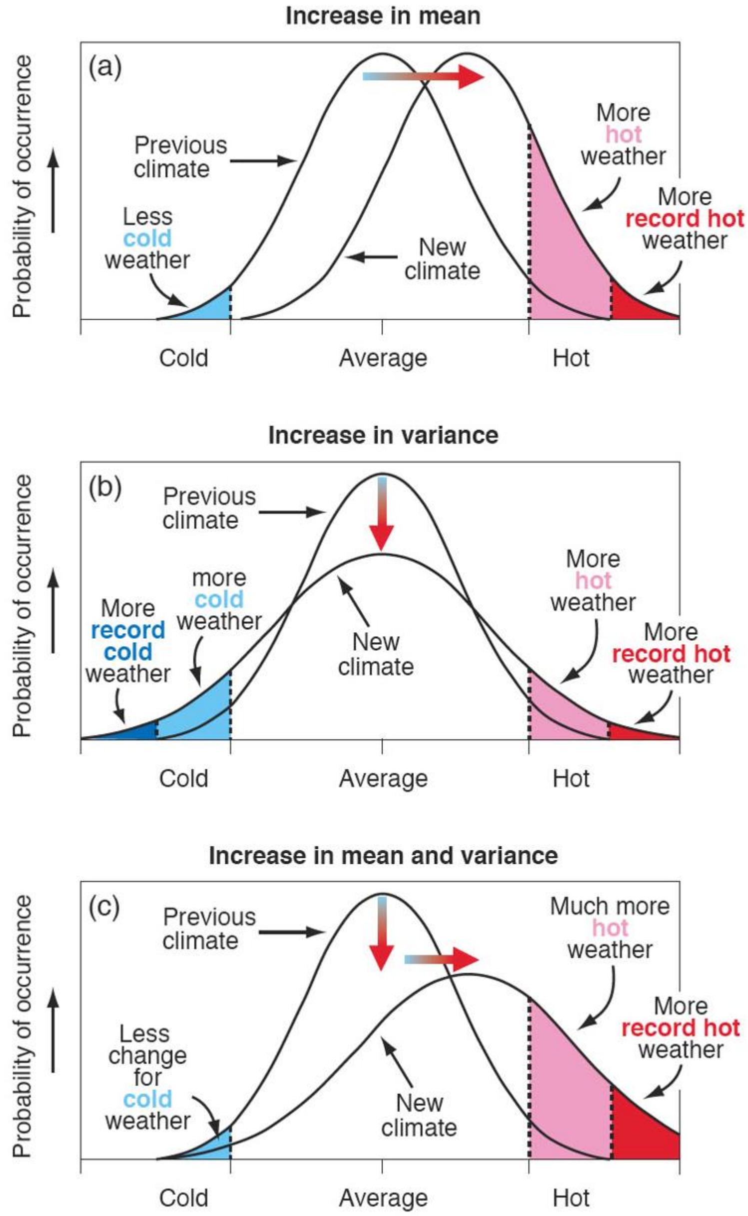

Figure 4. Schematic diagram showing a sample distribution of temperature in the historical climate and how it might change in future. The tails of the distribution indicate much colder or hotter temperatures than average and are less likely to occur. The horizontal axis shows temperatures ranging from cold to hot, while the vertical axis shows the probability of occurrence of these temperatures. Source*: Folland et al. (2001).*

1.4 Overview of climate model methodology, projections, and associated uncertainties

Our main tool for investigating future climate change is based on the same methods that inform one of science's greatest practical successes: the numerical weather prediction model. With appropriate modifications allowing for changing greenhouse gas forcing and the longer time scales involved, global climate models permit the simulation of myriad physical, chemical, and even biological processes and their complex interactions throughout Earth's atmosphere, land, and oceans. Key variables of interest are available through time and over a finite grid of points spanning the globe. Dozens of research groups around the globe have created their own climate models, each representing the Earth system in a slightly different way, such as the way clouds are simulated or how vegetation responds to carbon dioxide variations. When combined, the set of models is called a multi-model ensemble. Since each model's climate change projection represents an expert theoretical estimate at an uncertain future state, climate researchers interpret the ensemble as capturing a *range* of possible future climates. Figure 5 shows a diagram of how a multi-model ensemble is assembled and analyzed.

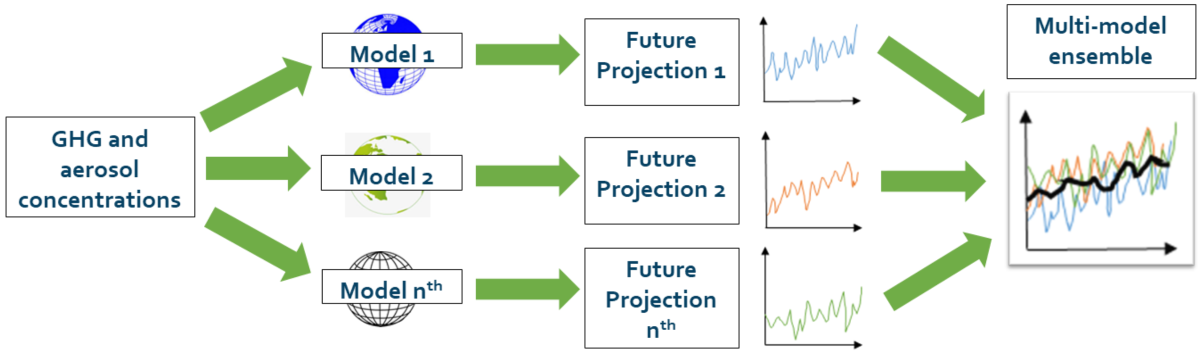

Figure 5. How a multi-model ensemble is produced from multiple GCMs. Given a future scenario of greenhouse gas (GHG) emissions or concentrations, future projections from a number of individual climate models are produced. Projections from multiple models define a range of possible future values for a specific variable, shown in the graphs, which can be averaged to produce an ensemble mean to characterize overall change. The number of models used is often 30 or more. Source: Adapted from ClimateData.ca Training Materials.

The standard suite of models used for international and national climate assessments come from the Coupled Model Intercomparison Project (CMIP). CMIP comprises a global effort to understand past and future climate change. These models use different future pathways of how greenhouse gas emissions may change in the future, called emissions scenarios. In the most recent intercomparison (i.e. CMIP6) models use Shared Socio-economic Pathways (SSPs) to describe how country-scale decision making and socio-economic factors, such as population growth and energy production, lead to different amounts of greenhouse gases in the atmosphere. The three most commonly used scenarios for running CMIP6 models are, ranked from low to high cumulative emissions over the century: SSP1-2.6, SSP2-4.5, and SSP5-8.5. In a previous intercomparison (i.e. CMIP5) models used analogous scenarios, called Representative Concentration Pathways(RCPs), which describe slightly different emissions pathways that lead to roughly similar amounts of warming by the end of the century (i.e., RCP2.6, RCP4.5, and RCP8.5). In this Overview, future projections information from both CMIP5 (Taylor et al., 2012) and CMIP6 (Eyring et al., 2016) are presented from various peer-reviewed studies and, in some cases, custom analyses. This is necessary because much of the research relevant to BC performed using CMIP5 models has not been repeated using results from CMIP6. Nevertheless, this research is still fully adequate for the purposes of climate change assessment. Table 1 shows a comparison of total carbon dioxide concentration and global warming by the late century for three RCP and SSP scenarios. See the *PCIC Primer: Understanding Future Climate Scenarios* for an accessible discussion of the differences between RCPs and SSPs (PCIC, 2024).

Table 1. Comparison of CMIP5 RCPs and CMIP6 SSPs for low, intermediate, and high emissions scenarios. Global average surface temperature change is relative to pre-industrial (1850-1900; IPCC, 2014; Lee et al., 2021). Carbon dioxide concentrations provided by Ouranos.

Emissions Scenario		Concentration of CO_2 by 2100 (ppm)	Global average surface temperature change in 2081-2100 (^oC)
High	SSP5-8.5	1135	+ 4.8
	RCP8.5	935	+ 4.3
Medium	SSP2-4.5	602	+ 2.9
	RCP4.5	538	+ 2.4
Low	SSP1-2.6	445	+ 2.0
	RCP2.6	420	+ 1.6

The use of multiple SSPs leads to a third type of uncertainty about future climate projections—in addition to natural climate variability and inter-model uncertainty—known as scenario uncertainty. Since scenario uncertainty concerns the unknown path of human development and has nothing to do with climate modelling per se, how to choose the “correct” scenario may not be obvious, as it involves other considerations. One way to account for this uncertainty is by providing information from more than one scenario, where it is available. It should be understood that climate model projections are sometimes only available for a single scenario, often a high emissions scenario, since this allows the envisioning of a “worst-case” outcome that can be helpful for policy decisions.

Alternatively, there is a way to avoid scenario uncertainty by relaxing our usual habit of presenting future projections at specific points in time. Imagine we ask: what value does a given climate model project for a variable of interest when global warming reaches a certain threshold value, say 2.5 ^oC? This allows information from any future scenario that reaches that global warming level (GWL) to be included, so no scenario needs to be chosen. The trade-off is that we must accept some uncertainty in the timing of the impact (connected to the variable of interest), since the timing of GWL = 2.5 ^oC differs in different scenarios. However, presenting climate projections in terms of GWL, rather than for fixed future time periods, has become a compelling way to simplify the presentation of future projections—and it is one way that we present results in this Overview as well. Results presented for GWL = 2.5 ^oC and GWL = 4.0 ^oC include models running both the SSP2-4.5 and SSP5-8.5 scenarios.

In projections up to the year 2100 over BC, natural climate variability and model uncertainty are the dominant uncertainties for most variables, with scenario uncertainty becoming the most important for temperature by the end of the century (Hawkins and Sutton, 2011).

Irrespective of these uncertainties, numerous analyses conducted throughout BC point to a number of common characteristics shared by nearly all model projections over all scenarios. Figure 6 summarizes these robust changes, which are described in greater detail in the sections below.

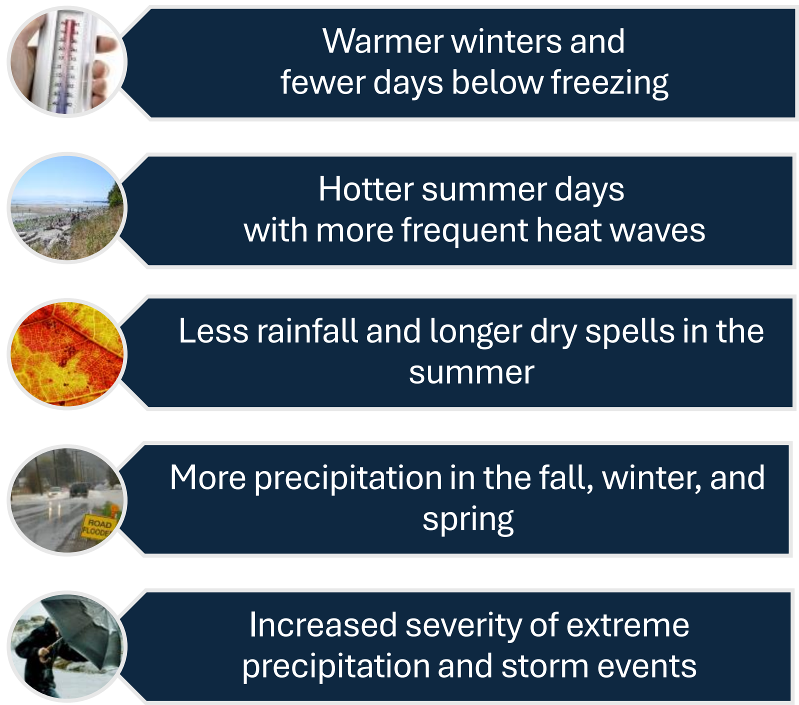

Figure 6. Broad features of climate projections for BC that are robust across climate models and scenarios from mid-.century (circa 2050s) onward.

1.5 Climatic hazard drivers and hazard identification

Climate observations and models give us an abundance of information about a range of variables, but often we are more interested in the impacts of changes in those variables, and especially their variability, on other systems. When impacts on humans, the wider ecosystem, or the built environment occur as the result of extreme weather events occurring over days, or persistent adverse climatic conditions, we refer to the corresponding climate variables as hazard drivers. Examples of hazard drivers occurring at the scale of days are extreme high temperatures (sometimes in concert with high humidity), heavy rainfall, and extreme wind. Corresponding hazards that might result from these drivers are heatwaves, flooding, and/or infrastructure or debris-related damage. However, most hazards (referred to as multi-variable hazards) have multiple drivers, meaning that focusing on one variable alone is not sufficient. Extended periods of below- or above-normal behaviour also count as hazard drivers: for example, low seasonal precipitation in concert with high temperatures can prompt both drought and wildfire hazards.

The Provincial Overview ultimately focuses on five climate-related hazards: extreme heat, wildfire, drought, riverine flooding and coastal flooding. Since many of these have common hazard drivers, we organize this Annex around these key drivers (climate variables) rather than the hazards themselves. In the summaries of climate variables that appear below, a brief review is given of the known characteristics of each variable and its expected change in BC in response to global warming. Subsequently, the focus shifts to specific hazards of interest for this Overview and their anticipated change in the coming decades. Figure 7 shows a schematic describing which hazard drivers influence the hazards addressed in this report.

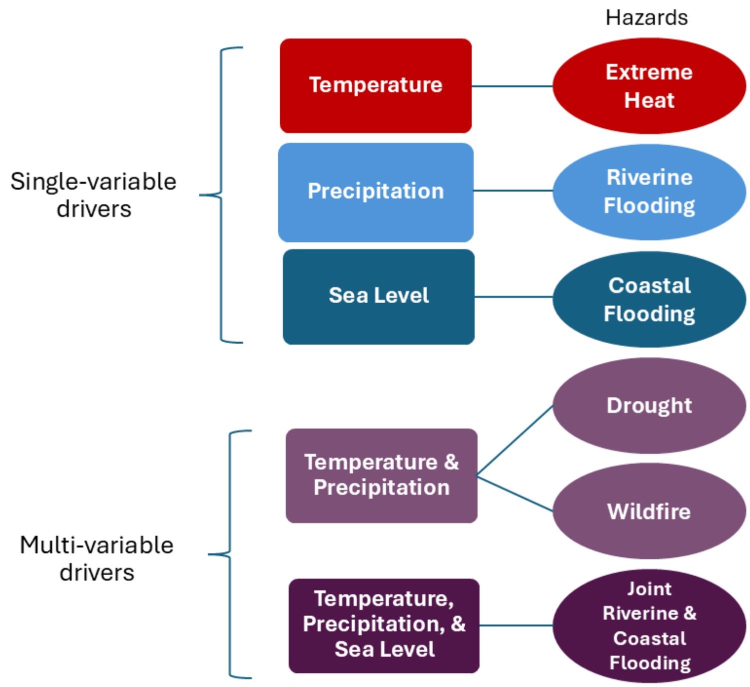

Figure 7. Flow chart describing which hazard drivers exert the most influence on the hazards described in this report.

2. Climate-related hazards of relevance to British Columbia

2.1 Temperature-related hazards

This section addresses historical and future-projected changes in average surface temperature and temperature extremes to better understand changes in the extreme heat hazard.

2.1.1 Overview of temperature variations across BC

In BC, the usual temperature gradient between southern and northern areas is strongly modified by physical geography. First, the bordering Pacific Ocean raises annual mean temperatures compared to interior areas, while second, annual temperatures are lower in the mountainous terrain covering much of BC. Figure 8 clearly exhibits these features, and much more detailed structure that largely reflects the complex network of river valleys throughout the province. While much of the BC coast is characterized by a mild year-round climate, the rest of BC exhibits a continental-style climate with large seasonal temperature variations, featuring hot summers and cold winters. Air is often trapped in steep valleys, and in summer this increases the intensity of experienced heat. The adjacent Pacific Ocean can bring cool breezes to coastal areas, but also occasional high-pressure ridges ("blocking highs") that stall over the province and manifest as extended and/or intense heatwaves.

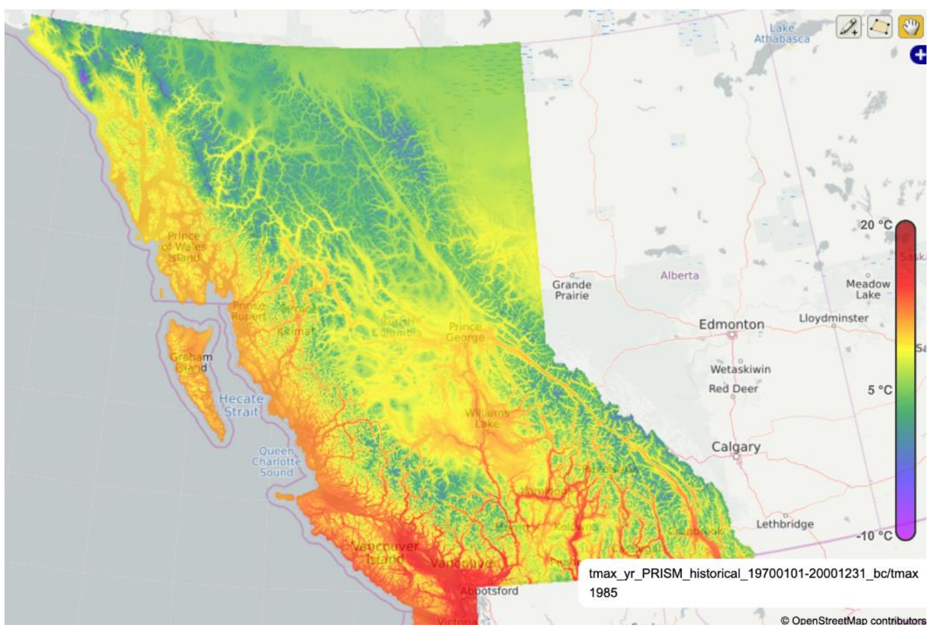

Figure 8. Observation-based map of mean annual temperatures across BC for the 1970-2000 period. Source: PCIC PRISM product, with a nominal horizontal resolution of 800 metres, as represented on PCIC's Data Portal. Note: selecting a climatological period of 1981-2010 or 1991-2020 would result in a map indistinguishable from this figure.

2.1.2 Historical temperature change in BC

To supplement the information provided in Figures 2 and 3 above, Table 2 below summarizes the changes in average surface temperature annually and seasonally across Canada and BC since 1948. The table shows that annual average surface temperature has risen 1.7 ºC in BC over this period. Both nationally and provincially, warming has been detected in all seasons, with the exception of fall in BC, and is nearly twice as large in winter compared to the other seasons.

Table 2. Historical temperature change in Canada and B.C. Observed changes in annual and seasonal temperature between 1948 and near-present, as determined from a linear fit to the data over the entire period. Data for Canada are from an updated Environment and Climate Change Canada gridded station data product (1948-2023; Wang et al., 2023), while those for BC are derived from PCIC's Provincial Climate Data Set (PCDS, 1948-2021; PCIC, 2024). Trends consistent with zero at the 5% significance level are shown in parentheses.

Region	Season	Mean Temperature Change (ºC)	Region	Season	Mean Temperature Change (ºC)
Canada	Annual	+ 2.1	BC	Annual	+ 1.7
	Winter	+ 3.5		Winter	+ 3.2
	Spring	+ 1.7		Spring	+ 1.6
	Summer	+ 1.7		Summer	+ 1.7
	Fall	+ 1.9		Fall	*(+ 0.83)*

Increasing mean temperature does not necessarily constitute a hazard. Typically, when thinking about hazards, we look at extremes. For example, impacts of intense heat were brought into stark focus during the unprecedented June 2021 extreme heat event in the Pacific Northwest region (Philip et al., 2022; White et al., 2023). This tragic 3-day event led to over 600 fatalities in BC (Egilson et al., 2022), mass-mortality of marine life, reduced crop and fruit yields, river flooding from rapid snow and glacier melt, and also set the stage for wildfires and post-wildfire debris flows (White et al., 2023).

2.1.3 Future projected temperatures and extreme heat

Figure 9 portrays the observed and future-projected annual mean temperature in BC for a selection of CMIP6 models running the low (SSP1-2.6), medium (SSP2-4.5), and high emissions scenarios (SSP5-8.5). In all three scenarios, temperatures are warmer than in the past. The trajectory of the various projections reinforces the message that historical conditions and/or trends do not constitute reliable guides for the future. For example, even under the medium emissions scenario, the projected *lower* limit of temperature change by the end of the century (just above 2 ºC) is warmer than the highest historical annual mean temperature (indicated by the solid black line).

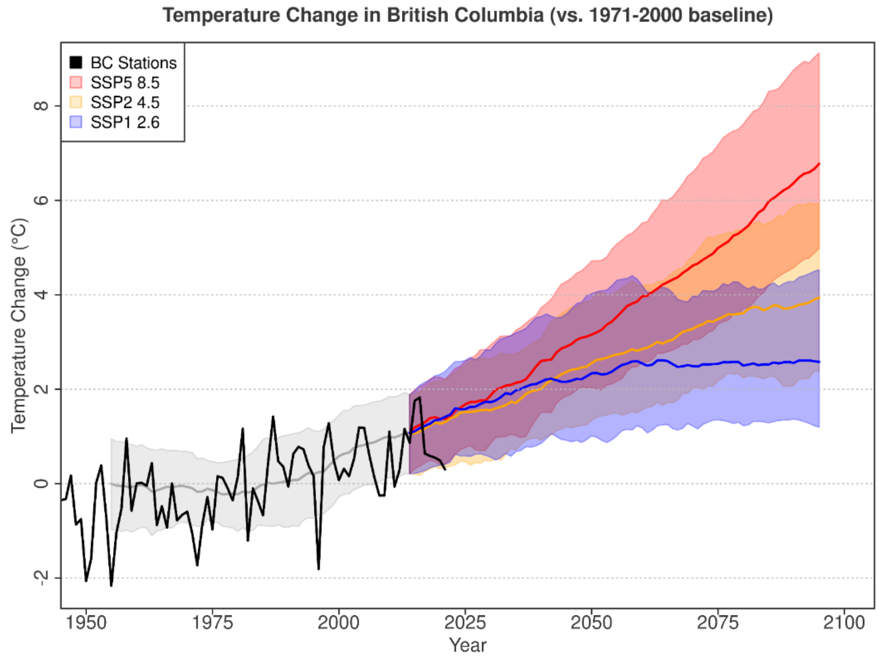

Figure 9. Model-simulated historical (grey) and projected temperature (colours) change for BC under three future emissions scenarios: low (SSP1-2.6; blue), medium (SSP2-4.5; yellow), and high (SSP5-8.5; red) (PCIC, 2023). Coloured lines are median values, while shaded bands show model ranges (percentiles). Changes are relative to the 1971-2000 mean temperature. BC-averaged historical data from the PCDS are shown by the black line.

Table 3 shows median values of projected annual average surface temperature and annual highest daily maximum temperature in BC for CMIP6 models under the moderate and high emissions scenarios, SSP2-4.5 and SSP5-8.5, respectively. Also shown are temperature changes relative to 1971-2000. Under SSP5-8.5, BC's temperature is projected to rise by nearly 3 ^{o}C, with an increase of 3.6 ^{o}C in annual highest daily maximum temperature by the 2050s (the 2041-2070 period). By the 2080s, average surface temperature is projected to increase by 6 ^{o}C, with an increase in annual highest daily maximum temperature exceeding 7 ^{o}C. Under SSP2-4.5, warming occurs more slowly, but the amount of warming by the 2080s (+3.5 ^{o}C) exceeds the amount of warming projected to occur by the 2050s under SSP5-8.5 (+2.9 ^{o}C). Since impacts are related to the magnitude of temperature change rather than its precise timing, these results suggest that effective climate adaptation planning can occur even in the presence of scenario uncertainty.

Table 3. Future-projected temperature change in BC. Values and projected in annual mean surface temperature and annual highest daily maximum temperature, averaged over BC, based on outputs from CMIP6 models. Results are presented for two future periods under two emissions scenarios (SSP2-4.5 and SSP5-8.5) and also in terms of global warming level (GWL).

		SSP2-4.5		SSP5-8.5		GWL	
Variable		2050s	2080s	2050s	2080s	+2.5	+4.0
Annual average surface temperature (^{o}C)	Value	3.7	4.9	4.4	7.4	4.2	6.3
	Change	+ 2.4	+ 3.5	+ 2.9	+ 6.0	+ 2.7	+ 4.8
Annual highest daily maximum temperature (^{o}C)	Value	28.5	30.4	29.5	33.1	29.2	33.5
	Change	+ 2.5	+ 4.5	+ 3.6	+ 7.1	+ 3.4	+ 7.7

The results in Table 3 demonstrate a useful alternative way of presenting future climate projections, namely, by de-emphasizing the precise *timing* of warming under different scenarios and instead focusing on the global warming level (GWL), that is reached. Since the severity of climate change-induced impacts tends to scale with GWL, presenting climate projections in this way, rather than for fixed future time periods, is a useful approach for impact and risk assessments. For this reason, Table 3, and many of the subsequent climate projections in this Overview, also includes results in terms of GWL. For example, if the GWL reaches 4.0 ^{o}C, then BC average and extreme temperatures are projected to increase by +4.8 ^{o}C and +7.7 ^{o}C, respectively.

As mentioned earlier, neither rising average temperatures over a long period nor daily high temperatures in a given year constitute a hazard. We need to consider a measure of extreme heat that has a known impact in the recent historical period, yet is relatively rare, that we would like to track in the future. For example, episodes of extreme temperature that persist over several days, or heatwaves, are a recognized threat to human health, ecosystems, and infrastructure. Low-intensity heatwaves are common and might occur every year, while rare heatwaves are of much higher intensity and often have a higher impact. Rare events are often described using return periods. For example, a rare event that occurs about once every 100 years in a long historical record is said to have a 100-year return period. This can also be expressed as a probability of occurrence, in any given year, of 1/100 or 1%. This is called the annual exceedance probability (AEP) or likelihood of the event. Alternatively, starting with an event of known intensity (for example, a specific temperature threshold), we can use the statistical theory of extremes to compute its corresponding return period.

Climate models can help us understand the intensity, persistence, and likelihood of extreme heat events, both in the recent historical period and in a future context under increasing greenhouse gas emissions. Here we consider a heat event characterized by a 3-day mean temperature that is so intense, and rare, that it is expected to occur only once every 50 years (AEP of 2%), on average. We denote this 3-day mean extreme temperature event hereafter by TM3. As a common resource for both historical and future-projected extreme heat events, we use an ensemble of 9 statistically downscaled and bias-corrected CMIP6 GCMs, with a horizontal resolution of ~10 km x 10 km, optimized for use over BC (PCIC, 2023). The time series of annual maximum TM3 are first computed for every grid cell in BC in the 1971-2000 reference period. The same procedure is then carried out for two future 30-year periods characterized by GWLs of 2.5 ^{o}C (reached roughly in the 2050s, but with the timing varying amongst models) and 4 ^{o}C (reached roughly in the 2080s). Each time series is then used in an extreme value analysis to derive intensity-frequency curves at every location in BC.

Figure 10 shows the simulated magnitude of TM3 over BC, both in the historical reference period (1971-2000; *left*) and in a projected 2050s climate (right).

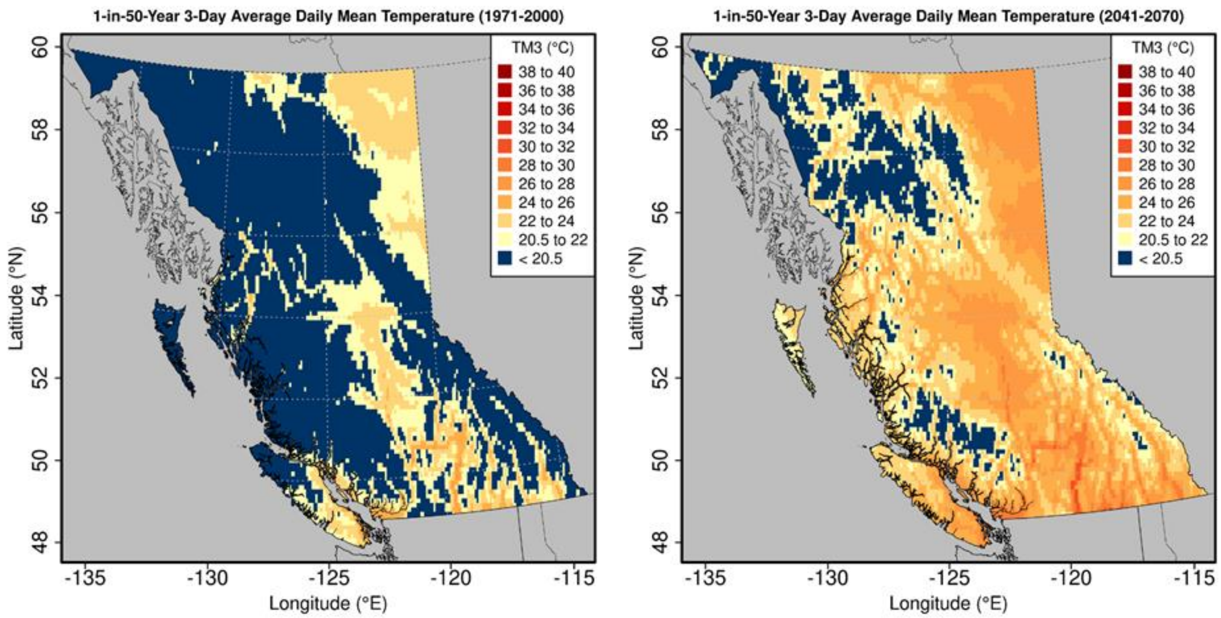

Figure 10: Mean temperature of a 1-in-50 year, 3-day heatwave event (TM3) in the historical period (1971 – 2000; left), and in the climate projected for the 2050s by an ensemble of downscaled CMIP6 models. Results for the median model are shown.

The left-hand panel of Figure 10 shows that in the simulated historical climate, the most intense 3-day heatwaves have a mean temperature of around 28 ^{o}C and occur in the far south of the province. Over a majority of BC's area, however, these 3-day temperatures do not constitute a hazard. These areas, shown in dark blue, have intensities of less than 20.5 ^{o}C, lower than the lowest threshold used for heat alerts anywhere in the province (see below). The right-hand panel of Figure 10 shows that in the projected mid-century climate, these rare and intense 3-day heatwaves have noticeably higher mean temperatures than in the historical period, exceeding 30 ^{o}C in some areas. More importantly, the area of the province exposed to extreme heatwaves increases markedly in the 2050s, covering a majority of the area of BC.

To set appropriate intensities for extreme heat events in BC, the Provincial Heat Alert and Response System (HARS) uses specific temperature thresholds for five regions across the province (McLean et al., 2018). These thresholds vary by region and describe a sequence of three consecutive daytime high and nighttime low temperatures (day-night-day; Figure 11), similar to, but of shorter duration, to the TM3 definition used for Figure 10. In both observations and in the CMIP6 models, we found that the HARS thresholds are rarely exceeded in the 1971-2000 period over most of BC. In the model results, for example, the thresholds were

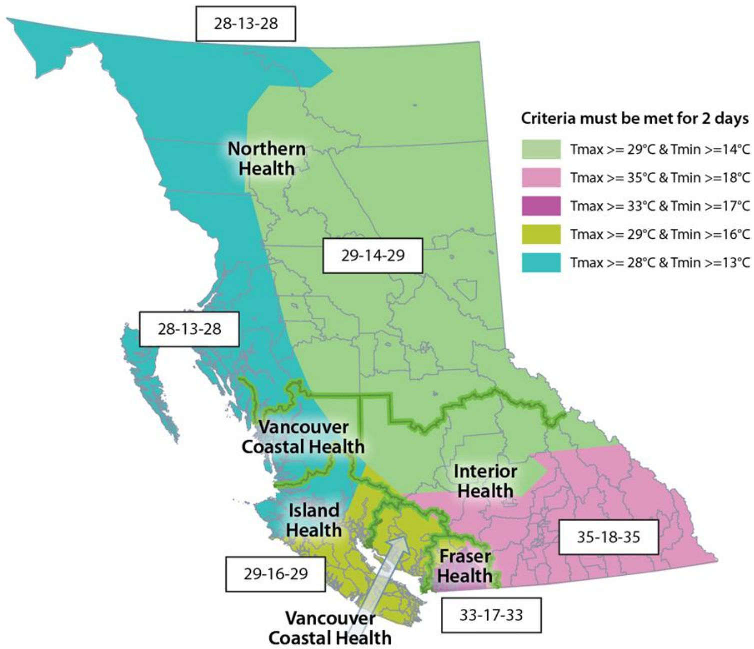

Figure 11. BC HARS thresholds across BC (BC Provincial Heat Alert and Response System, 2023).

never reached over 95% the province, and the frequency was just 5 times or less at the few locations where they were exceeded over the 30-year period. This means that from the perspective of using climate model projections to examine extreme heat in the future, using HARS directly as our definition for an extreme heat event is not practical (since we need at least some events to analyze in the historical period). Instead, we use the HARS thresholds to screen out any TM3 events that would not be expected to constitute a hazard, based on the average of daytime and nighttime HARS thresholds in each region:

Northwest: 20.5 ^{o}C

Northeast: 21.5 ^{o}C

Southwest: 22.5 ^{o}C

Southwest inland/Fraser: 25 ^{o}C

Southeast: 26.5 ^{o}C

By setting TM3 equal to these thresholds in each region, we can determine the return period of these TM3-HARS thresholds over BC. As shown in the left-hand panel of Figure 12, in the median model there is a very low probability (return period > 100 years in most locations) of TM3-HARS exceedance (extreme heat events) over most of the province in the historical period. Under 2.5 ^{o}C of global warming (approximately the 2050s, middle panel of Figure 12), however, extreme heat events are projected to occur once every 2 to 30 years over about half of the province. Exceptions are the southwest inland and southeast regions (see Figure 11 for regional definitions), which still show few TM3-HARS events (except in broad, deep valleys where warm air can be trapped) due to the high HARS thresholds there (i.e., 25 ^{o}C and 26.5 ^{o}C, respectively). By 4 ^{o}C of global warming (approximately the 2080s, right-hand panel of Figure

12), TM3 (or extreme heat) events surpassing the HARS thresholds are projected to occur at least once every 10 years over most of the province, and every 1 to 2 years over about half of BC.

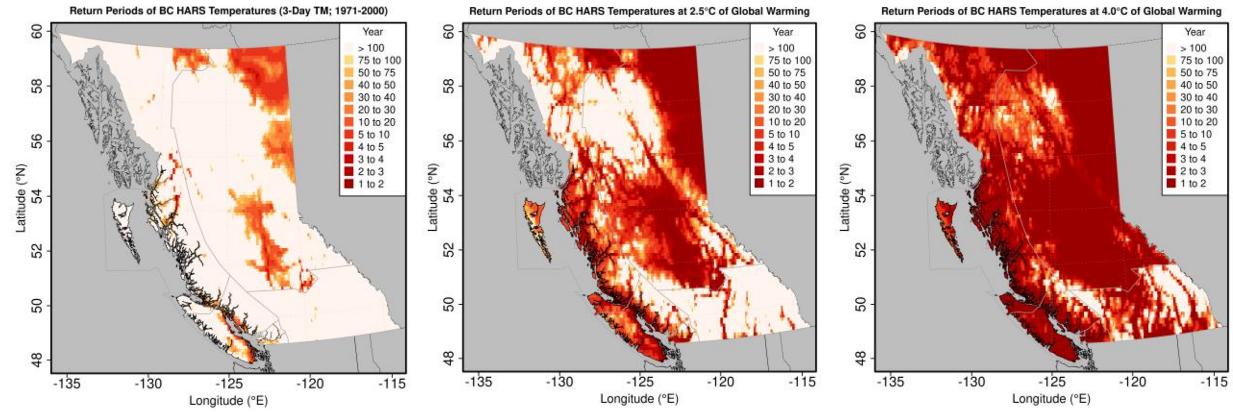

Figure 12. Return periods of TM3-HARS events for the historical period (1971 – 2000; left), GWL of 2.5 ^{o}C (middle), and GWL of 4 ^{o}C (right). Results for the median model are shown.

These return period results are converted to annual exceedance probability (AEP) in Figure 13, for the assessment of likelihood change. As shown in the left-hand panel, extreme heat events exceeding the average day-night-day HARS thresholds are very rare (AEP < 1%) over most of the province, apart from the northeast and central BC. At 2.5 ^{o}C of global warming (middle panel of Figure 13), extreme heat events become possible or likely over about half the province, and almost certain in selected areas. By 4.0 ^{o}C of global warming (approximately the 2080s), extreme heat events become likely to almost certain over most of the province.

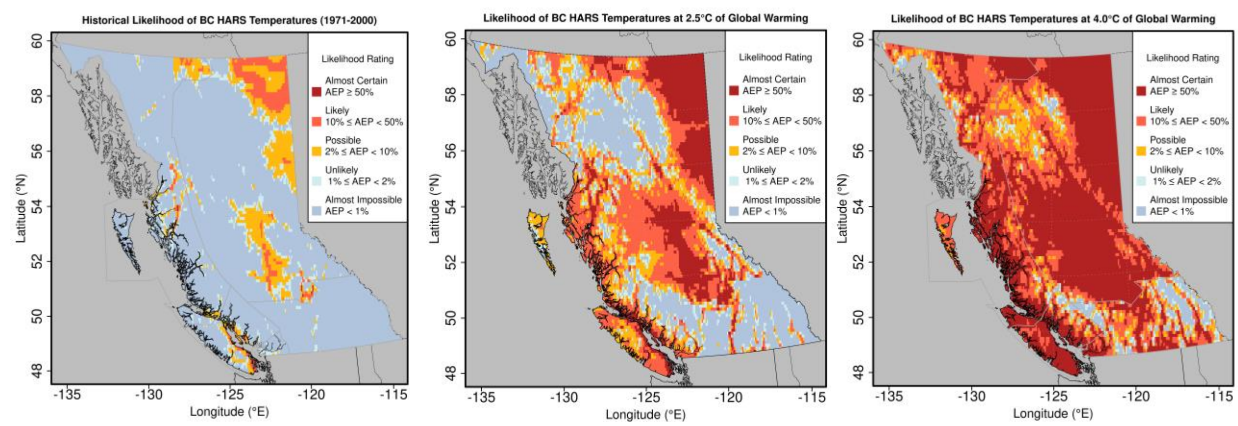

Figure 13. Likelihood rating for 3-day extreme heat events using BC HARS thresholds for the historical period (left), GWL of 2.5 ^{o}C (middle), and GWL of 4 ^{o}C (right).

2.2 Precipitation and hydrologic hazards

This section characterizes historical precipitation patterns, riverine flooding hazards and drought over BC and the surrounding area before moving to a discussion of future-projected changes.

2.2.1 Overview of precipitation variations across BC

Like temperature, the spatial variation of precipitation in BC is closely tied to the complex topography of the region and proximity to the Pacific Ocean. Relatively warm, moist air transported eastward from the Pacific Ocean is lifted over the steep topography of the west coast, resulting in precipitation falling on the windward slopes of the Coast Mountain range. The process repeats in inland ranges all the way to the Rockies, with drier conditions on the leeward mountain slopes, interior valleys, and plateaus. Figure 14 shows the spatial variation of total annual precipitation across BC, which clearly reflects this strong topographic influence. The character and distribution of BC's hydrologic basins are strongly determined by this map, in combination with the temperature variations previously shown in Figure 8.

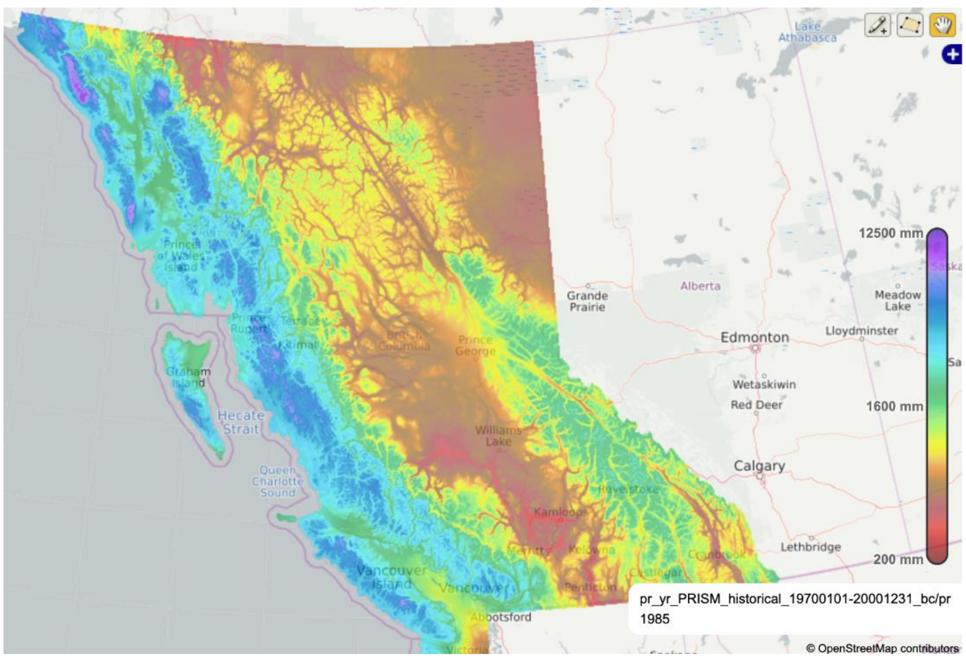

Figure 14. Observation-based map of total annual precipitation across BC for the 1970-2000 period. Source: *PCIC PRISM product, with a nominal horizontal resolution of 800 metres, as represented on PCIC's Data Portal.*

The seasonality of precipitation across the province varies considerably according to region (see the review of Moore et al., 2010). Most of the precipitation in coastal and adjacent regions (Haida Gwaii, Sunshine Coast, Greater Vancouver and the Fraser Valley, and Vancouver Island) falls as rain between October and March, but substantial snowpacks are present at higher elevations. In central (Fraser, Thompson and Okanagan) and southeast (Kootenay and Upper Columbia) BC, smaller amounts of precipitation are delivered more evenly throughout the year, mostly as snow in the winter months. These areas experience cold winters with substantial snowfall, especially in mountainous areas where perennial snowpacks and glaciers are found. The Northern Region, encompassing areas east of the Alaska Panhandle to Alberta, experiences cold winters with moderate snowfall during the winter months. Throughout the BC interior, slightly more precipitation falls in spring and summer than in fall and winter, unlike near the BC coast. Summers in coastal BC are much drier than in the cold season, but with comparable rainfall amounts to interior areas at the same latitude.

A significant fraction of BC's precipitation is delivered by atmospheric rivers (ARs), long and narrow plumes (> 2000 km long by a few 100 km wide) of water vapor originating over the Pacific Ocean that make landfall along the entire west coast of North America (Neiman et al., 2008). Based on data from 1948 to 2016, some 15 to 35 ARs arrive on the BC-Alaska panhandle coast each year, most in autumn and the fewest in spring (Sharma and Dery, 2020a). Over recent decades, ARs are estimated to contribute as much as 20% of total annual precipitation in coastal BC, decreasing to 11% and 6% in the interior ranges (Columbia and Rockies, respectively; Sharma and Dery, 2020b). This contribution varies by season, and differs between rain and snow: for example, roughly 50% of rain in November-December is brought by ARs. ARs should be considered an important component to natural precipitation variability in the region, that have had a mainly beneficial impact on BC's ecohydrology and water supply (principally via snowpack maintenance). Only occasionally do they create conditions that lead to flooding, with the most notable recent example being the November 2021 combination of two successive ARs that penetrated farther than usual into the Fraser Valley (Gillett et al., 2022).

2.2.2 Precipitation variability, trends, and extremes

Table 4 summarizes observed changes in annual and seasonal precipitation in Canada and BC over the past seven decades. While there is no evident trend in annual mean precipitation in BC over that time, increases in spring (+14%) and fall (+18%) have been detected. There is a suggestion of a decrease in winter, when most precipitation falls in the province, and an increase in summer; but these changes are not statistically significant. In Canada as a whole, precipitation has increased significantly in all seasons except winter.

Table 4. Historical precipitation change in Canada and BC. Observed changes in annual and seasonal precipitation in Canada and BC between 1948 and near-present, as determined from a linear fit to the data over the entire period. Data for Canada are from an updated Environment and Climate Change Canada gridded station data product (1948-2019; Wang et al., 2023), while those for BC are derived from PCIC's Provincial Climate Data Set (PCDS, 1948-2021; PCIC, 2024). Trends consistent with zero at the 5% significance level are shown in parentheses.

Region	Season	Change in precipitation (%)	Region	Season	Change in precipitation (%)
Canada	Annual	+ 12.6	BC	Annual	*(+ 5.3)*
	Winter	*(+ 3.2)*		Winter	*(− 13.3)*
	Spring	+ 17.4		Spring	+ 13.6
	Summer	+ 15.8		Summer	*(+ 9.8)*
	Fall	+ 16.3		Fall	+ 18.2

These historical trends occur on top of natural climate variability, which is significantly larger for precipitation than for temperature (compare Figures 2 and 3). Two examples of this that operate at scales far larger than BC are the El Nino-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO). Their influence has been found to be strongest in winter, which may explain the weaker trends found in that season.

2.2.3 Hydrologic response to precipitation and temperature

The spatial variations of temperature and precipitation in the province shown in Figs. 8 and 14, respectively, result in three main types of watersheds found in the province: rain-dominated (or pluvial), snowmelt-dominated (or nival), and hybrid (Eaton and Moore, 2010). Rain-dominated regimes are found primarily in coastal lowland areas and at lower elevations of the windward side of the Coast Mountains. In rain-dominated basins, the temporal variability of streamflow closely follows that of rainfall, though moderated by the effects of water storage and movement in soils, groundwater, lakes, and wetlands. In these basins, the highest monthly discharge values occur in November and December, when the most intense frontal storms impact the BC coast. The lowest monthly flows occur in July and August, when few such weather systems make landfall, at least in the southern half of the province. Examples of rain-dominated basins are the Campbell and Carnation Creek watersheds on Vancouver Island.

Snowmelt-dominated regimes are found in the higher-elevation zones of the Coast Mountains and the interior plateau and mountain regions. In these zones, winter precipitation mainly falls as snow and is stored until melting commences in spring. As a result, these regimes exhibit low flows throughout winter, peak flows in May to July, and low flows again during late summer and fall as a consequence of low precipitation and depletion of the snowpack water supply. A majority of BC's area falls into the snowmelt-dominated category, with two of the largest examples by area being the Peace and Columbia basins. A subcategory, nival-glacial watersheds, have their headwaters in glaciated regions at high elevation. These watersheds experience peak flows slightly later in the year, June through August, and higher flows in summer as compared to purely nival basins due to glacier melt. In nival basins the glacier melt contribution can be particularly important in maintaining flows during warm dry summers (Jost et al., 2012). Observations collected over the last several decades (negative mass balance and volume loss) indicate that glaciers throughout BC are out of equilibrium with the current climate (Moore et al., 2009). This trend is expected to continue, and possibly accelerate, with continued warming of the climate (Clarke et al., 2015).

BC's remaining watersheds fall into a hybrid category, exhibiting features of both rain- and melt-dominated streamflow regimes. Most of these basins are found in coastal and near-coastal regions of the province, with examples being the Skeena and Stikine basins.

As is the case for precipitation, decadal-scale trends in streamflow are sensitive to the phase of ENSO and the PDO. During the negative (cold) phase of the PDO, and La Niña periods, winters in western Canada are typically cooler and wetter than average, with a larger snowpack at high elevations leading to higher annual discharge than average. Roughly opposite behaviour occurs during the positive (warm) PDO phase and occurrences of El Niño. As for the effect of decadal climate variability on streamflow, Curry and Zwiers (2018) demonstrated that at the main outlet of the Fraser River Basin at Hope over the last century, annual peak flows in years with negative (cold) PDO phase are significantly larger than in years with positive (warm) PDO phase. Similar results were found for ENSO (i.e. higher peak flows in La Niña years).

2.2.4 Riverine flooding

Riverine flooding occurs when water overflows the banks of an established watercourse in response to the exigencies of seasonal climate, land surface state and weather extremes. The factors affecting streamflow, and the potential for riverine flooding, vary considerably by region due to BC's diverse topography and climatic zones. In BC, drivers of flooding include intense and/or prolonged rainfall, rapid snowmelt, ice jams, glacial melt, natural or artificial dam outburst flooding, steep creek processes (debris flood or debris flow) or rain-on-snow events. For all types of floods, smaller, localized events tend to occur more frequently than larger, widespread events, with the greatest destructive potential where flows are deeper and fast-moving. Using broad regional definitions for convenience, we can summarize the dominant flood types as:

- Southwest Coast Region (rainfall-dominated floods)
- Interior Central Region (rainfall and snowmelt mixed floods)
- Southeast Region (snowmelt-dominated floods)
- Northern Region (snowmelt-dominated floods)

In the Southwest Coast Region, snowpacks at mid-elevation normally melt quickly in late spring-summer, usually without adverse impacts. Flooding is typically driven by heavy rainfall brought by Pacific frontal storms, including ARs. One type of AR, so-called Pineapple Express storms carrying warmer than average moist air, can deposit substantial rain on snow at higher elevations, which in turn can trigger rapid onset flooding and debris flows in smaller catchments flanked by steep valley slopes. During a period of intense rainfall, localized flash floods can occur when the ground is saturated and not able to absorb the water quickly enough, resulting in high runoff that can cause rivers and streams to overtop their banks. This region is also subject to coastal flooding due to storm surge and/or high tides, particularly in tidal deltas.

In the Interior Central Region, flooding is typically driven by snowmelt during the spring freshet; however, some basins to the west are exposed to rainfall brought by frontal systems and ARs (e.g., the Coldwater River watershed), resulting in flooding sometimes exacerbated by rain-on-snow events. In the Southeast Region, snowmelt-driven floods typically occur in the spring while glacier melt contributes to summer streamflow. Finally, in the Northern Region, snowmelt-driven floods typically occur in late spring. Rivers in this region are often influenced by ice cover during the winter months, which can produce ice-jam flooding. In these three regions, the potential for flooding increases during conditions with an above-average snowpack, if the snowmelt is compounded by runoff from heavy rainfall, or if a sudden thaw of the accumulated snow occurs. In the latter case, if the ground is still frozen, water from snowmelt does not infiltrate into the soil and runs off over the ground surface into streams or rivers.

The most extreme flooding event on the Fraser River occurred in May 1894, when rapid snow melt caused river levels to rise dramatically, triggering flooding from Agassiz to Richmond, BC. Past historical flood events have occurred on major BC rivers in 1894, 1948, 1972, 2017, 2018, 2020 and 2021 in response to snowmelt, rainfall and mixed (rain-on-snow) triggered events, reflecting the complexity of flood processes in BC. In 2007, the Great Coastal Gale caused extensive coastal flooding due to intense rainfall and hurricane-force winds over a three-day period in December. Flooding resulted in extensive property damage, road closures, and disruptions to transportation and utilities. Across the diverse BC landscape, floods occur every year on smaller watercourses with more localized impacts.

Detailed hydroengineering simulations of historical floods and scenarios of extreme floods have provided valuable information on extreme flooding in the Lower Fraser Basin. The hydraulic models used in these studies can be more closely tailored to actual floodplain characteristics, including engineered structures such as spillways and dikes in specific locations along watercourses. The Lower Mainland portion of the FRB is arguably the best studied floodplain in BC in this respect. A recent summary report gathered the results from several such studies comprising the Lower Mainland Flood Management Strategy initiative (Fraser Basin Council, 2023). The 2019 Hydraulic Modelling and Mapping Project developed a 2D hydraulic model for the lower Fraser River floodplain and examined 20 scenarios encompassing a range of extreme riverine floods (50- to 500-year), coastal storm surge (50- and 500-year), various dike breach scenarios as well as mitigation options. In a scenario where an event of the same magnitude as the 1894 Fraser River flood of written record (estimated as a 500-year event in a stationary climate) occurred, the Project found that ~20 dikes would likely "be overtopped (and potentially more to fail in other ways) and flood nearly 300 km2 of land."

The most notable recent flooding event in the Fraser Basin was prompted by a sequence of two ARs that made landfall in November 2021. The ARs brought two days of intense precipitation to southwestern BC that resulted in extreme flooding and extensive geomorphic change in watersheds across the lower Fraser River watershed. The AR was a rain-on-snow event in many areas where the streamflow generated by rainfall was augmented by melting snow, prompted by a rapid rise in temperature (Gillett et al., 2022). The flood event resulted in widespread landslides, washouts, bank erosion, and channel avulsions. The impacts were exacerbated by overflow of the Nooksack River in the Sumas Prairie near Abbotsford, extensive damage to infrastructure such as Highway 1, Highway 8, and associated bridges, extensive flooding in the communities of Merritt and Princeton, and impacts to First Nations communities in the Nicola Valley.

2.2.5 Future-projected precipitation and hydrologic extremes

Table 5 shows model results from CMIP6 (future amount and percent change, relative to the 1971-2000 baseline) for total annual precipitation and 5-day annual maximum precipitation over BC under the moderate (SSP2-4.5) and high (SSP5-8.5) emissions scenarios. While the annual precipitation increases by 9% (2050s) to 13% (2080s) under SSP5-8.5, the 5-day maximum amount increases by 13% (2050s) and 26% (2080s). This is consistent with other results found regionally throughout BC insofar as measures of extreme precipitation increase at a faster rate than mean values under warming (PCIC, 2024). As for temperature, while precipitation increases are smaller under SSP2-4.5 than SSP5-8.5, projections for SSP2-4.5 for the 2080s exceed those projected under SSP5-8.5 for the 2050s. Alternatively, if the GWL reaches 4.0 ^{o}C, then BC average and extreme precipitation are projected to increase by +12% and +19%, respectively.

Table 5. Future-projected precipitation change in BC. Values and projected changes (in percent) for annual mean precipitation and 5-day cumulative extreme precipitation over BC, relative to 1971-2000, based on outputs from CMIP6 climate models. Results are presented for two future periods under two emissions scenarios (SSP2-4.5 and SSP5-8.5) and also in terms of GWL.

		SSP2-4.5		SSP5-8.5		GWL	
Variable		2050s	2080s	2050s	2080s	2.5	4.0
Mean total annual precipitation	Amount (mm)	1360	1407	1395	1452	1367	1433
	Change (%)	+ 6.2	+ 9.8	+ 8.9	+ 13.3	+6.7	+ 11.8
5-day annual maximum precipitation	Amount (mm)	94	98	96	107	94	101
	Change (%)	+ 10.6	+ 15.3	+ 12.9	+ 25.9	+ 10.9	+ 18.6

Future-projected streamflow

Due to the complexity of the riverine flooding hazard, increases in precipitation do not necessarily imply increases in flooding—the entire water cycle, land-atmosphere interaction and the timing of climatic drivers needs to be considered (Sharma et al., 2018), in addition to regional geography. The interactions between these complex processes are fairly well captured by global, regional and hydrologic process models, which explains why our knowledge of projected hydrologic behaviour under climate change largely comes from such models. Several of the main results are summarized in this subsection.

The influence of climate change on snowpack in some nival watersheds in BC was recently studied by Shrestha et al. (2021), who analyzed results from an ensemble of regional climate model simulations (of scale ~45 km x 45 km, driven by a CMIP5-class global climate model). The projections indicate a steep decline in maximum annual snowpack in the warmer coastal/southern basins (i.e., Skeena, Fraser and Columbia), a moderate decline in an interior basin (i.e., Peace), and little to no change in colder northern basins (i.e., Liard). The authors also assessed the sensitivity of annual maximum snowpack to below-normal, near-normal, and above-normal seasonal temperature and precipitation finding that snow drought primarily occurs under above-normal temperature and precipitation. This implies that the projected temperature-driven decline in snowpack dominates over the cold season precipitation increases over BC (Table 5).

Other studies have consistently projected a tendency toward earlier maximum snowpack and earlier peak flows in snow-dominated basins as warming proceeds (e.g., Schnorbus et al. 2014; Islam et al., 2017, 2019; Shrestha et al., 2019). The most detailed evaluations of the impact of projected climate change on basin-scale hydrology use process-based, high-resolution hydrologic models employing approximations of actual streamflow networks. The studies of Shrestha et al. (2012, 2019) and Schnorbus et al. (2014) are particularly relevant to BC basins, although some use older emissions scenarios. In their study of the nival Liard basin in northeast BC, Shrestha et al. (2019) noted mixed results for the magnitude of annual maximum streamflow (modest increase or decrease depending on location), but earlier maximum snowpack and earlier peak flows. Annual low flows also increased in future in this subarctic basin—but this is not often found in studies of BC's other, more southerly or coastal basins.

In BC basins where substantial snowpack declines are projected by mid-century, earlier and reduced snowmelt results in earlier peak flows (by up to 4 weeks) and reductions in peak freshet flows (up to −20%), with some variation by basin and emissions scenario (Figure 15; Schnorbus and Cannon, 2014; Islam et al., 2017, 2019). Such reduced flows may reduce the flood risk during early summer, but also imply reduced summer water supply—all things being equal. However, these projections reflect median model behaviour over 30-year periods, meaning that peak flows similar to historical values can still occur in individual years even into mid-century, due to natural climate variability.

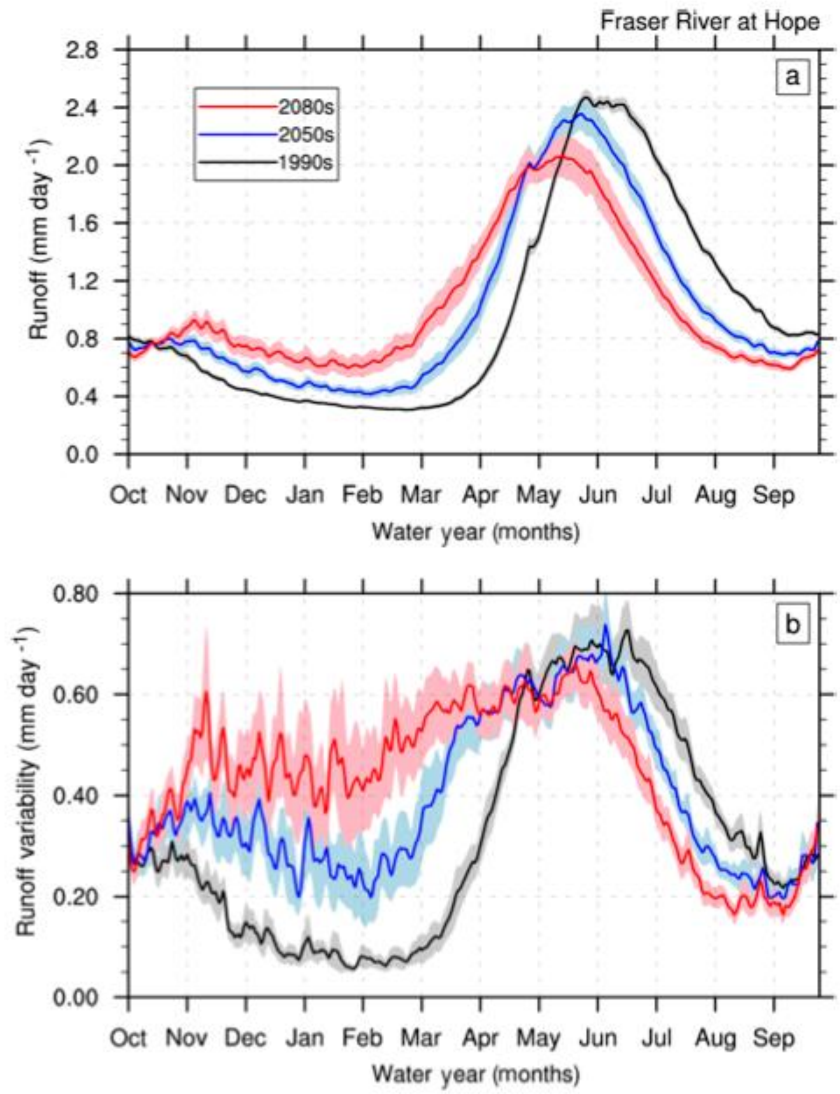

Figure 15. Simulated daily runoff (normalized discharge) mean (a), and variability (b) for the Fraser River at Hope. Black, blue and red curves represent the multi-model mean for the 1990s, 2050s and 2080s, respectively, under the RCP8.5 scenario. Shading represents inter-model spread, as indicated by a 5–95 % model range. From Islam et al. (2019).

When it comes to extreme flooding, the Fraser River Basin (FRB) is arguably the best studied in the province. Hydroclimate models have been applied to the basin as a whole, and hydraulic modelling studies of the lower floodplain portions were also conducted. An analysis of hydrologic model simulations over the FRB focusing on rare extremes (Schnorbus and Curry, 2019) suggest changes in the magnitude of a 200-year freshet peak flow at Hope ranging from −10% to +20% (model range) by end-of-century, with a positive median projection irrespective of emissions scenario. The frequency of extreme floods is projected to increase in future periods, but the details are scenario dependent. Under a medium emissions scenario, the return period of a 200-year event decreases to less than once in 50 years by mid-century, with a further decrease to around once in 30 years by end-of-century. Under high emissions, faster snowmelt results in more frequent high freshet flows at mid-century than at late century, when snowpacks become depleted. Under high emissions, the historical 200-year freshet flow becomes a 50- to 100-year event by mid-century, rising to a greater than 100-year event by end-of-century.

Another possible consequence of climate change is hydrologic regime change. Under strong warming, annual peak flows in snow-dominated basins, which currently occur exclusively during the freshet, may begin to occur during the cold season, particularly in coastal or coastal-adjacent basins like the FRB. Climate model ensembles project substantial increases (10-20% by end-of-century; Zhang et al., 2019) in fall and winter precipitation over historical norms. One consequence of this is enhanced runoff and river discharge in the cold season compared to present-day (Figure 15). Some modelling studies indicate that the FRB may begin to transition to a hybrid (snow-rain) behaviour where cold season peak discharge exceeds freshet flows in some years (Erler and Pelletier, 2017; Curry et al., 2019)—but not all studies agree on that point (Islam et al., 2017; Schnorbus and Curry, 2019). Nevertheless, there is broad agreement amongst model projections that large cold season events that are rare in the historical climate (a 1-in-200-year event) will become more frequent by mid-century (less than a 1-in-20-year event) under a moderate emission scenario and more frequent still (less than a 1-in-10-year event) under a high emissions scenario.

Finally, the response of glaciers to warming, and the associated streamflow changes in glaciated basins in BC, have been the subject of several modelling studies. Loukas et al. (2002a,b) modelled streamflow changes in the Illecillewaet River in the Columbia Mountains of BC for a future climate scenario and assuming a one-third reduction in glacier area. These results suggest a slightly increased glacier contribution to streamflow in May and June and a decreased contribution in July to September. The more recent modelling studies of Stahl et al. (2008) and Tsuruta and Schnorbus (2021) included a more explicit transient glacier response to climate change scenarios. Stahl et al. (2008), in modelling the Bridge River in the south Coast Mountains under a high emissions scenario, showed a dramatic decrease in glacier area and decreased streamflow throughout the melt season. Tsuruta and Schnorbus (2021) modelled the impact of glacier retreat in the Mica basin, which drains the Rocky and Columbia Mountains in the headwaters of the Columbia. By end of century under the RCP8.5 scenario, they too found an increased glacier contribution to streamflow in winter and spring and a decreased contribution in summer and fall.

2.3 Sea level rise and coastal flooding

Sea level is a sensitive indicator of climate change, as it responds to global warming both directly, via the heating and consequent expansion of seawater, and indirectly, via the loss of land-based ice due to increased melting.[1] Thermal expansion of seawater and glacier mass loss have resulted in 79% of total global mean sea level (GMSL) change from 1901 to 2018 (Fox-Kemper et al., 2021). Glacier mass loss primarily includes melt from the Greenland and Antarctic ice sheets and a smaller contribution from glaciers. Global ocean surface temperature increased by approximately 0.9ºC between 1850-1900 and 2020 (IPCC, 2021; Fox-Kemper et al., 2021), with the most rapid rate of increase occurring since 2012 (Climate Reanalyzer, 2024). A significant, increasing trend of ocean heat content determined from temperature measurements has also been established.

Figure 16 shows recent data on GMSL change from the U.S. National Oceanic and Atmospheric Administration (NOAA), spanning 1880 to 2023. The rate of sea level rise since 1993 displayed in the figure is near the upper end of sea-level projections from comprehensive global climate models used in the AR4-WGI (Church and White, 2011). According to the IPCC Sixth Assessment Report: Summary for Policy Makers (AR6-SPM;IPCC, 2021):

> Global mean sea level increased by 0.20 [0.15 to 0.25] m between 1901 and 2018. The average rate of sea level rise was 1.3 [0.6 to 2.1] mm yr^{-1} between 1901 and 1971, increasing to 1.9 [0.8 to 2.9] mm yr^{-1} between 1971 and 2006, and further increasing to 3.7 [3.2 to 4.2] mm yr^{-1} between 2006 and 2018 (high confidence). Human influence was very likely the main driver of these increases since at least 1971.

The ice sheet melt contribution from Greenland and Antarctica to GMSL rise was four times larger between 2010 and 2019 than from 1992 to 1999, making glacial mass loss the largest contributor to GMSL rise from 2006-2018.

[1] Melting sea ice does not contribute to sea level rise, as the ice was already floating, displacing its own weight in water.

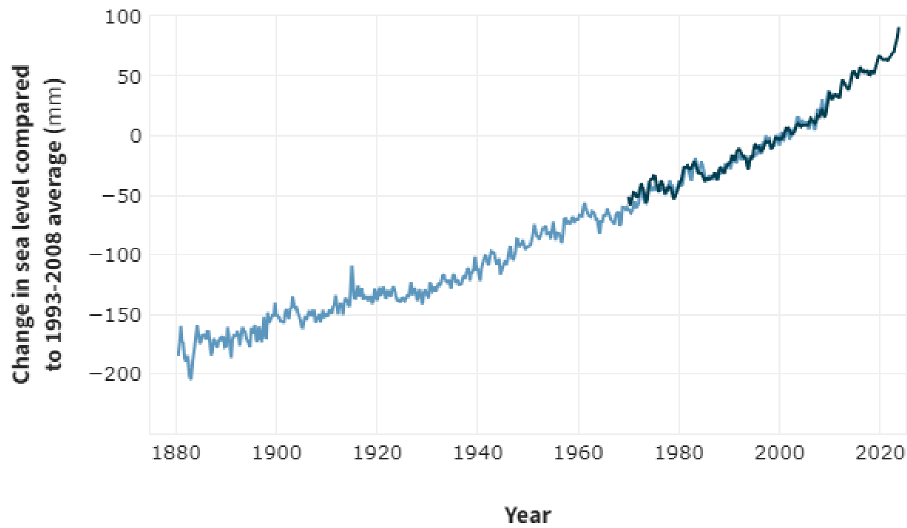

Figure 16. GMSL from 1880 to 2023 (Lindsey, 2022) from Church and White (2011; light blue line) and from 1970 to the near-present from the University of Hawaii Fast Delivery Sea level dataset (dark blue; access: https://uhslc.soest.hawaii.edu/data/?fd). Values are sea level change relative to the 1993-2008 average.

Figure 17 shows a map of sea level change around the world between 1993 and 2022. In some ocean basins, sea level has risen by 15-20 centimeters (blue-shaded contours). Also shown on the map are differences between *local* sea level change at specific coastal locations and the global mean value (coloured dots). Observed sea level change relative to a local, land-based frame of reference is called relative sea level (RSL). Drivers of RSL change include changes in Earth gravity (resulting from interactions between terrestrial ice and seawater), absolute sea level rise, and vertical land motion. The latter encompasses changes from tectonic deformation of the Earth's crust, land subsidence or uplift, and glacial isostatic adjustment (Kopp et al. 2015; Rovere et al. 2016; Fox-Kemper et al., 2021). The map shows that local rates of RSL change can be larger (due to geological processes like ground settling) or smaller than the global average (due to processes like the centuries-long rebound of land masses from the loss of ice-age glaciers). BC lies within a larger area of northwestern North America where the land surface is still rebounding from the last glaciation, meaning that RSL is rising more slowly in some locations than in others, or even falling slightly, due to the complex interplay of processes.

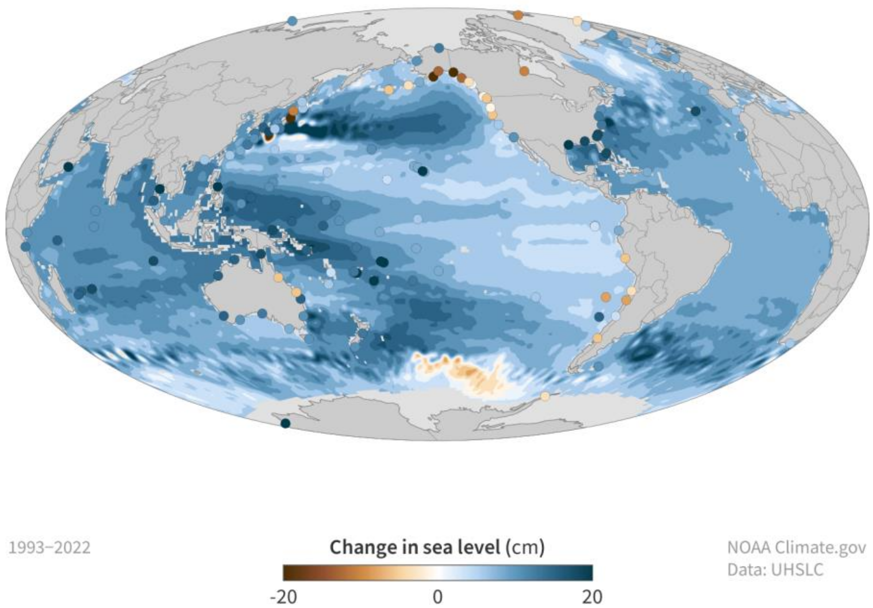

Figure 17. Sea level rise measured at specific locations on land from 1993 to 2022. Map by NOAA Climate.gov (Lindsey, 2022) based on data provided by Philip Thompson, University of Hawaii.

Two independent means of measuring sea level are available. Tidal gauges measure RSL at points along the coast, while satellite instruments (radar altimeters) measure absolute sea level over nearly the entire ocean surface. Many tidal gauges have collected data for more than 100 years, while satellite measurements began in the early 1990s.

Long-term tidal gauge measurements indicate that GMSL has risen by an average of 1.7-1.8 mm per year during the 20th century (Church and White, 2011), while satellite data indicate a higher mean rate of RSL rise of 3.2 ± 0.4 mm per year during the 1993-2010 period (Church and White, 2011; Cazenave and Remy, 2011). This amounts to a total GMSL rise since 1880 of approximately 20 cm or 8 inches. Continuing sea level rise is virtually guaranteed in the coming decades, due to warming that will occur as the ocean adjusts to the thermal forcing from existing greenhouse gas levels.

2.3.1 Global sea level projections

According to estimates in the IPCC AR6 Summary for Policymakers (IPCC, 2021), the likely global mean sea level rise by 2100 (compared to a reference period of 1995-2014) is 0.32–0.62 m under the low GHG emissions scenario (SSP1-2.6); 0.44–0.76 m under the moderate GHG emissions scenario (SSP2-4.5); and 0.63–1.01 m under the high GHG emissions scenario (SSP5-8.5), where the ranges indicate the spread across model projections under a given scenario. With somewhat reduced confidence, the AR6-SPM included projections for an extended period to 2150, which gave upper limits of 0.99 m (low emissions); 1.33 m (moderate emissions); and 1.88 m (high emissions). Finally, the authors commented that, due to uncertainty in ice-sheet processes that are not explicitly included in most global climate models used in the AR6, upper limits of 2 m by 2100 and 5 m by 2150 cannot be ruled out.

Figure 18 shows historical and future-projected GMSL change relative to 1900 for a number of emissions scenarios, including an additional low-likelihood, high impact scenario including ice-sheet instability processes that are highly uncertain, a scenario that cannot be ruled out based on current knowledge.

This scenario (sometimes referred to as SSP5-8.5+) is projected to result in more than +0.7 m of additional GMSL rise above the highest emissions scenario, SSP5-8.5, by 2100.

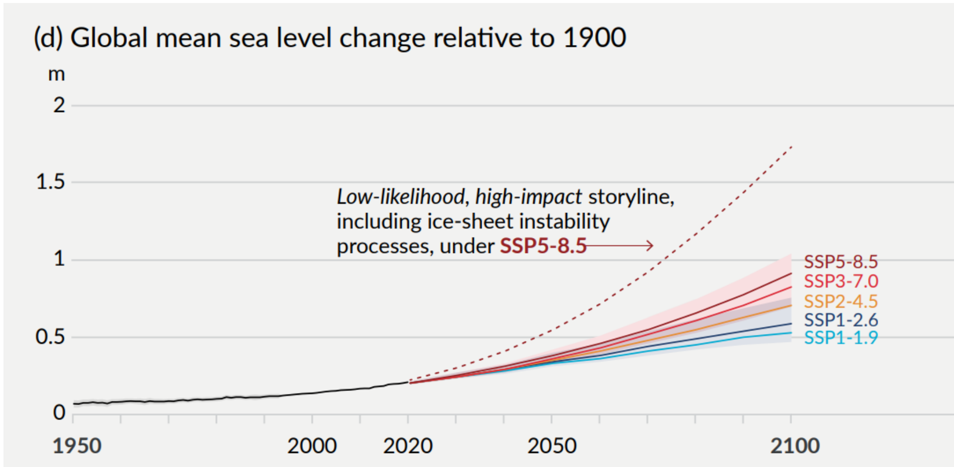

Figure 18. GMSL change relative to 1900 (SPM.8d, IPCC, 2021). Historical changes are observed using tide gauges pre-1992 and satellite altimeters afterward. Future projections are assessed using CMIP, icesheet, and glacier models. The mean change for five emissions scenarios is shown, including likely ranges for two of the scenarios (SSP1-2.6 and SSP3-7.0). The dashed curve shows the results of a low-likelihood outcome of the high emissions scenario (SSP5-8.5), which includes high impact ice-sheet processes that are very uncertain and thus cannot be ruled out.

2.3.2 Regional sea level projections

GMSL provides one perspective for understanding sea level change, however more relevant to a coastal flood risk perspective is how sea level change varies locally. RSL projections for a given location can vary significantly from GMSL projections as the drivers of RSL have a complex spatial pattern (Schnorbus and Curry, 2019). This section will highlight RSL projections for a single BC location of interest, near the mouth of the Fraser River. Additional information for the rest of coastal BC, using the same background climate data sources and based on the more comprehensive dataset of James et al. (2021), may be accessed at ClimateData.ca.

Figure 19 shows RSL projections under three scenarios for the mouth of the Fraser River (near Point Atkinson) from an unpublished study based on CMIP5 models (Schnorbus and Curry, 2019). In all three scenarios the water level increases relative to the past. The most extreme increases in water level are seen under scenario RCP8.5+ (the CMIP5 equivalent of SSP5-8.5+), with increases greater than 1.5 m by 2100 at the high end of the very likely range. The greatest differences in water level between scenarios are seen at the end of the century where uncertainty in the projections is also highest.

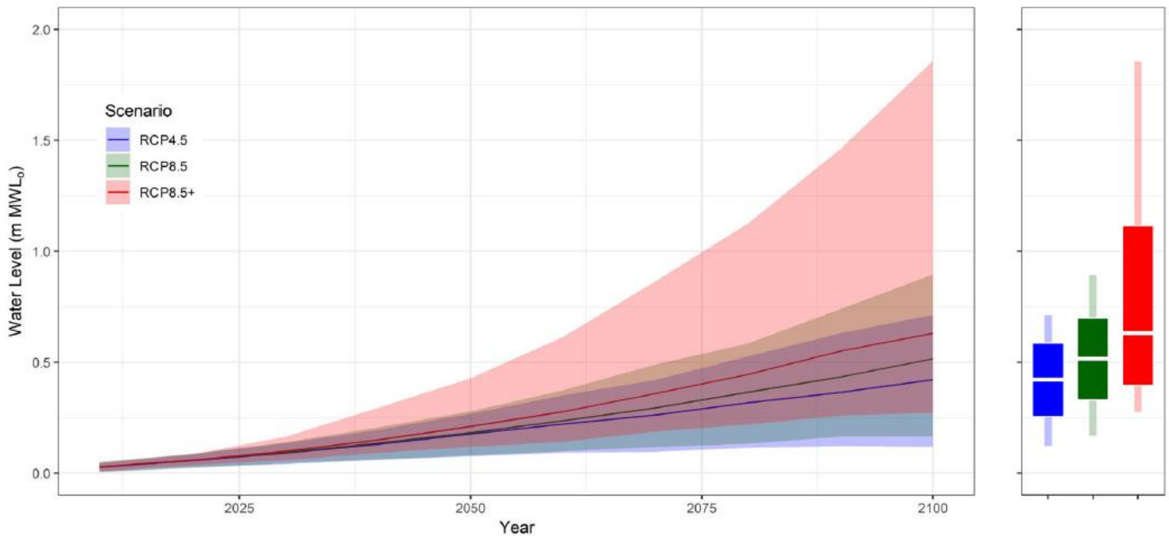

Figure 19. Relative sea level projections of three scenarios for the mouth of the Fraser River (Schnorbus and Curry, 2019). The left panel shows a time series of projected sea level rise for the 21st century. Solid lines show the median and shaded areas show the very likely range. The right panel shows the median (white line), likely (thick bars), and very likely (thin bars) ranges for 2100.

Figures 20 and 21 show projections for the return period of annual extreme water levels during the cold season (October to March) for 2050 and 2100, respectively (Schnorbus and Curry, 2019). Extreme water levels result from the combination of mean sea level, tides, storm surge, and wind-waves[2] (Rasmussen et al. 2018; Vousdoukas et al. 2018). By 2050, a historical 100-year extreme sea-level event is expected to occur every 4 to 5 years under all three scenarios (Figure 18). By 2100, these events are projected occur nearly every year under a high emissions scenario (Figure 19). For long return period events, there is little difference between projected sea level extremes in 2050 (i.e., all scenarios overlap in Figure 18) but by 2100 there is some divergence between the projected water levels from different scenarios.

[2] Extreme water levels are estimated by summing future-projected changes in relative sea level and historical tide gauge observations that reflect tides and storm surge. Tide gauges do not capture high-frequency behaviour such as wind-waves. The return level-return period curves shown in Figures 20 and 21 result from an extreme value analysis of the EWL time series. See Schnorbus & Curry (2019) for further details.

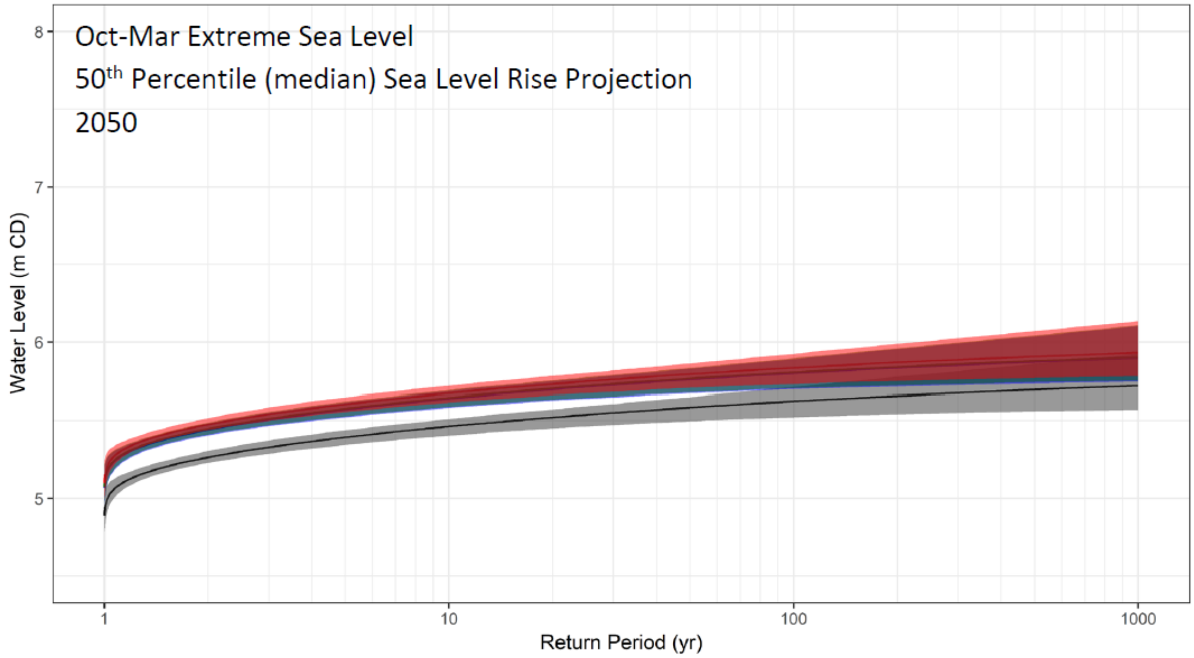

Figure 20. Projected return periods of cold season extreme water level in 2050 (Schnorbus and Curry, 2019). Results for the historical period are shown in grey, RCP4.5 in blue, RCP8.5 in green, and RCP8.5+ in red. The range is shown by shading and medians by solid curves.

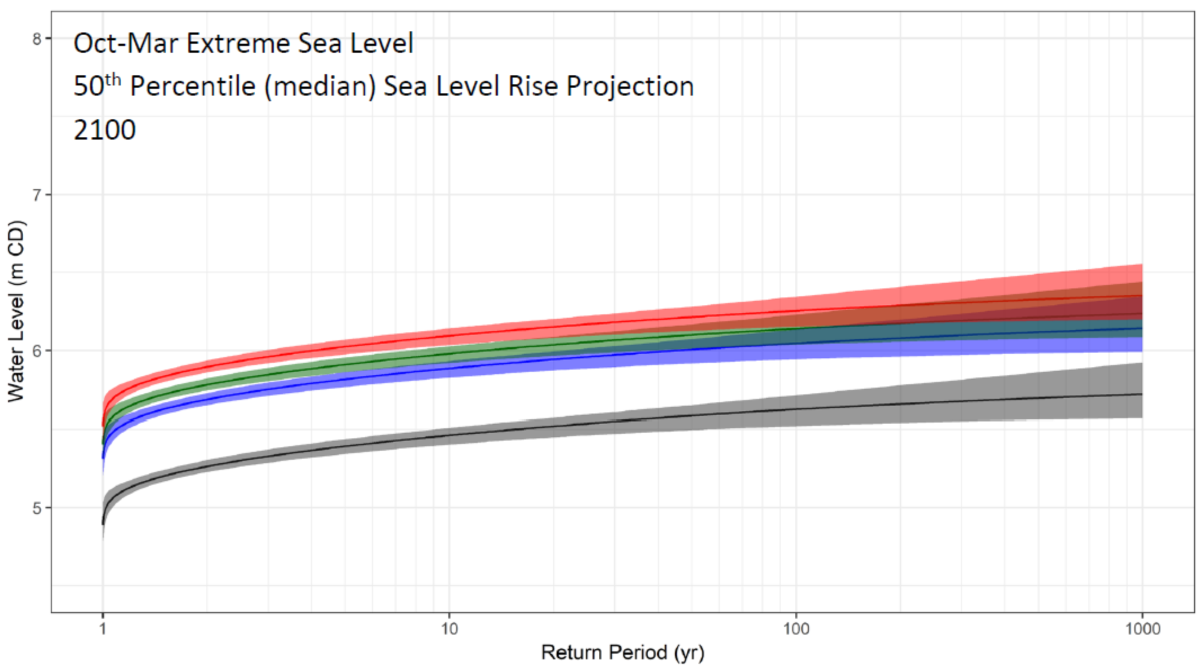

Figure 21. Same as Figure 20 but for 2100 (Schnorbus and Curry, 2019).

RSL projections are available for all of coastal Canada from ClimateData.ca on a 10 km x 10 km grid, using the same background climate data sources and based on the more comprehensive dataset of James et al. (2021). Isaacson (2022) recently provided an analysis of these results for BC. Based on RSL projections from ClimateData.ca, by the year 2100, Caswell Point off the west coast of Haida Gwaii is projected to see increases in RSL by +66 cm and +140 cm under RCP8.5 and RCP8.5+, respectively. In Victoria, RSL is projected to increase +20cm by 2050 and +57 cm by 2100 under RCP8.5.

2.3.3 Coastal flooding

With regard to flooding, estimates of RSL rise are not informative in and of themselves; what matters is the amount of sea level rise relative to typical flood levels at a given location. In a region such as the Florida coastline, ten-foot storm surges are sometimes seen, and thus ten inches of sea level rise may not necessitate unprecedented adaptation measures for those communities. Such measures may be necessary, however, in a coastal city that has only ever experienced two-foot surges, and where only inches separate the once-in-a-decade flood from the once-in-a-century one. It is important to understand that due to the inevitability of some additional warming in future, flood probabilities based on historical data will increase, even without assuming any change in the frequency and/or intensity of major landfalling storms (which is actually quite difficult to reliably detect in many climate model simulations).

Flooding is a common occurrence along the coastline of British Columbia. Coastal flooding occurs when sea waters rise and inundate the land along coastlines in response to different climatic factors, weather conditions, or land use changes. The factors affecting coastal flooding vary considerably by region due to BC’s diverse topography seasonal climatic patterns and incidence of intense landfalling storms. In BC, drivers of flooding most often occur due to wind-driven storm surge and wave action, sometimes augmented by high tides. The potential for tsunamis also exists due to ongoing seismic activity in the surrounding ocean, but they are rare. Each of these phenomena occur on top of more gradual sea level change in response to global warming. BC’s southern coastline is characterized by low-lying areas such as river deltas, estuaries and coastal plains that are naturally more prone to flood inundation, especially during winter storm surges or high tides. BC’s North Coast is often characterized by rugged terrain with fjords and steep coastal cliffs that are vulnerable to erosion, landslides, and other rainfall-driven hazards during a flood event. Land use changes such as urbanization, forestry and alteration of natural drainage systems can exacerbate the risk of coastal flooding.

During the fall and winter, BC’s coast intercepts intense storms which are often accompanied by strong winds and heavy rainfall. These conditions can generate storm surges, which are a temporary increase in sea level that can result in coastal inundation and flooding, especially in areas that are close to sea level. Some areas of BC’s coastline can experience significant tidal variations between high and low tides. Extreme high tides, known as king tides, are naturally occurring based on the earth's gravitational pull, and when combined with storm surge conditions, can increase the risk of coastal flooding. When king tides coincide with storm surges or high winds, they can lead to localized coastal flooding and erosion of natural barriers that protect coastal communities such as beaches, dunes, and wetlands. King tides today help imagine more extreme tidal variations due to future sea level rise.

Extreme coastal flood events are largely governed by the occurrence of high tides and storm surges during the winter months, rather than peak flows during the spring as occurs for riverine floods. However, heavy rainfall or atmospheric rivers (ARs), combined with snowmelt, could exacerbate coastal flooding during the fall and winter months, particularly in areas with a tidal influence such as the Fraser River valley.

Coastal flooding can occur extremely rapidly. The Great Coastal Gale of 2007 is an example of a historical coastal flood event that brought heavy rain and hurricane-force gusts over a three-day period in December that resulted in widespread flooding across the Pacific Northwest and BC. The flooding resulted in property damage, road closures, disruptions to transportation and utilities and impacts to coastal communities in BC. Because BC is located within an active seismic zone, the potential for earthquakes and tsunamis can cause sudden coastal flooding along the coast. Tsunamis are triggered by seismic events such as underwater earthquakes or landslides but are historically rare.

2.4 Multi-variable climate hazards

This section provides an overview of hazards that are influenced by more than one climate variable, including drought, wildfire, joint coastal and riverine flooding, and extreme rainfall and landslides.

2.4.1 Drought

Drought is a consequence of joint conditions in precipitation, soil moisture, atmospheric evaporative demand (AED)[1], and runoff that result in consistently low moisture conditions over a period (IPCC Sixth Assessment Report, hereafter IPCC-AR6, Seneviratne et al., 2021). Drought occurs naturally in the climate system when there is a prolonged dry period relative to what is typical in a region. In BC, seasonal drought typically results from a combination of insufficient snow accumulation in winter, prolonged hot temperatures, and/or low rainfall. The three main drought types comprise meteorological drought (MET), agricultural-ecological drought (AGR/ECOL), and hydrologic drought (HYDR). For meteorological drought, a commonly used index known as the Standardized Precipitation Evapotranspiration Index (SPEI) uses precipitation and AED to determine drought severity. The other drought types are affected by meteorological drought but include additional components. For example, agricultural-ecological drought is informed by variations in soil moisture and/or land use, while hydrologic drought is sensitive to changes in water storage (for example, snowpack) and the type and timing of precipitation over the year.[2]

While climate impact drivers such as extreme heat and precipitation can be considered at any scale in time or space, drought is inherently broad in terms of its extent and duration. For example, the SPEI is typically computed and analyzed over periods ranging from 1 to 48 months. The development and persistence of past droughts in North America has also been linked to modes of large-scale climate and sea surface temperature variability like ENSO and the PDO (Dai, 2013).

[1] AED is the maximum amount of evapotranspiration that can occur from land surfaces that are not water-limited, and depends on temperature, wind speed, solar radiation, and humidity.

[2] The periodically updated, province-wide drought levels appearing on BC's Drought Information Portal are mainly informed by measures of hydrologic drought.

The link between rising air temperatures and water scarcity on the surface and in soils and vegetation results from basic physics. As the atmospheric temperature increases, the capacity of the air to hold moisture rises exponentially. This increases AED, and since plant conductance and near-surface flows respond more slowly, dries out soils and vegetation. This subsequently reduces how much water in the system is available to recharge groundwater and surface water levels, at least locally (the moister atmosphere will eventually deposit any excess water vapour elsewhere). This process occurs on all timescales: routinely during the warm season, acutely during a heatwave, and more slowly (but directionally) on longer timescales when temperatures are consistently above normal and precipitation is below normal.

To our knowledge, a comprehensive analysis of these drought types over BC specifically has not been conducted. However, some specific results are available. As reviewed earlier (Table 4) observations since around 1950 do not indicate a decreasing trend in precipitation over the province in any season; rather, some seasons display significant increases. However, the fraction of precipitation falling as snow has decreased in some areas, with implications for hydrologic drought (see below). According to the IPCC-AR6 (Table 11.21), there is "medium confidence" that AGR/ECOL drought has increased since 1950 in Western North America; however, this large region mostly encompasses the Western U.S. and only the southern edge of BC, so it is likely dominated by the strong drought signal seen in the former region (Diffenbaugh et al., 2015). On longer time scales, analyses of tree-ring data from interior (Starheim et al., 2013) and coastal BC (Coulthard et al., 2016) indicate a higher frequency and severity of droughts prior to the 20th century.

Regarding hydrologic drought, reduced snowpack caused by increasing temperatures in winter (Table 2) and a higher fraction of precipitation falling as rain are likely to be increasingly important in BC's nival and hybrid watersheds. In any given year, a substantially reduced snowpack in a watershed can lead to hydrologic drought in the warm season. Decreasing annual maximum snow depth and snow cover duration have been detected over much of BC since 1981, with the exception of the southern Rockies and parts of the BC Interior (Brown et al., 2021; Mudryck et al., 2018). Between the early 1960s and mid-2000s, Najafi et al. (2017) noted decreases in cumulative summer streamflow at the major outlets of two snow-dominated basins (Fraser and Peace Rivers) and one hybrid basin (Campbell River). A review article (Bonsal et al., 2019) noted a significant decreasing trend in 1-day minimum flows in southwest BC watersheds between 1970 and 2005, but more recent analyses seem to be lacking. It should be kept in mind that while "snow drought" may occur in individual years, it needs to occur over a multi-year period before a long-term trend in behaviour can be discerned. On longer timescales, there is evidence of 12 multi-year snow droughts since 1719 in southwestern BC that ranged from 2 to 5 years, most occurring before 1914, with the last three 2-year snow droughts occurring in 1934-35, 1941-42 and 1980-81 (Mood et al., 2020).

To the south of BC, Diffenbaugh et al. (2015) analyzed historical climate observations in California since the late 1800s, finding that precipitation deficits in California were more than twice as likely to yield drought years if they occurred when conditions were warm. Moreover, they found that the occurrence of drought years has been greater in the past two decades than in the preceding century, coinciding with a similar temperature rise over recent decades to that seen in BC. Again like BC, this has occurred despite the lack of any significant change in precipitation in recent decades. However, the authors established that the probability that precipitation deficits co-occur with warm conditions and the probability that precipitation deficits produce drought have both increased. This may allow us to anticipate how drought occurrence may be affected by future-projected temperature and precipitation in a similar region such as BC.

Since interactions between land and atmosphere are integral to drought, it is important to also consider how changes in the land surface may exacerbate this hazard. For example, soil compaction, removal of wetlands, stream diversion (straightening), soil hydrophobicity following wildfire, or increases in impervious surface (e.g., pavement) area all reduce water infiltration capacity and increase overland flow. This diverts water from the soil thereby reducing the residence time of water within the system. Any impact that reduces storage can result in water scarcity later in the year. This is particularly important in snow-dominated systems where water supply in the warmer months depends on cold season precipitation.

While historical records are invariably incomplete making a definitive assessment of trends in drought itself difficult, several resources are now available for monitoring and evaluation over the more recent period. The BC Drought Information Portal provides up-to-date information on drought severity province-wide, in addition to historical drought information starting in 2015, while the Canadian Drought Monitor provides similar information across Canada, with historical information dating back to 2007. Drought conditions in BC are currently assessed using many drought indicators, including basin snow indices (BC River Forecast Centre, 2024), seasonal volume runoff, 30-day precipitation percentiles, and 7-day average streamflow (British Columbia Drought and Water Scarcity Response Plan, 2023).

Future-projected drought

Historically, periods of low precipitation have been viewed as the dominant driver of drought. However, as described above, in a warming world the demand side of drought potentially has a greater influence than in the past. Hence, even under moderately reduced precipitation, the prevalence of warmer than average temperatures can initiate or prolong existing drought, through several different pathways. As emphasized in recent research, “indicators based solely on precipitation have limitations in capturing drought persistence owing to rainfall high variability. Additionally, in snow-dominated regions, precipitation indices might fail to capture intricate snow dynamics such as rapid snowmelt and low flow conditions during the dry season” (AghaKouchak et al., 2023). BC is, in large part, just such a region. So while we begin this section with a review of future projections of traditional drought indices (e.g., SPEI), we then summarize work on drought from the more comprehensive, hydrologic, perspective.

Starting with projections of short-term (3-12 month) drought indicators from climate models, Tam et al. (2019) analyzed CMIP5 projections of SPEI across Canada. The authors noted that in summer and especially fall under the medium (RCP4.5) and high (RCP8.5) emissions scenarios, conditions are expected to become steadily drier in southern BC in the coming decades. While water surpluses are projected in winter and spring (due to the precipitation increases appearing in Table 5), these are not sufficient to compensate for the warm season deficits. The example of Summerland, BC is highlighted, where the 12-month SPEI indicates that moisture deficits dominate over surpluses throughout the remainder of the century, regardless of emissions scenario. Elsewhere in BC, projected changes in SPEI are small except along the northern Pacific coast, which becomes less drought-prone by the late 21st century under all scenarios. The most severe drought conditions are projected in autumn in southwestern BC.

Reliable information about longer duration droughts (i.e., lasting up to a decade or longer) is more difficult to obtain from climate models. A decade-long drought like the 1930's Dust Bowl in the U.S. has been estimated to occur once or twice per century over western North America based on paleoclimate records stretching back ~2000 years (Woodhouse and Overpeck 1998). There is also evidence of longer-duration, multidecadal droughts prior to the 1600s, but with more uncertain frequency due to the limited length of the observed record. This limitation also applies to most climate model simulations, which typically span just a few hundred years. Moreover, research has shown that the long-timescale precipitation variability in climate models differs from observation-based estimates, in that they likely underestimate the frequency of droughts lasting a decade or more (Ault et al., 2014).

Recognizing this shortcoming, Ault and coauthors (2014) applied a statistical correction, based on paleoclimate data, to the precipitation distribution of CMIP5 models to obtain improved estimates of historical and projected long-term drought frequency and risk. Risk was calculated as the percent of the total number of corrected simulations that produce at least one decadal or multidecadal drought. Although interest was confined to the western U.S., their results show a clear pattern of decreasing risk from south to north up to the U.S.-Canada border and into southern BC, where the risk is limited to < 20% for a decadal drought and < 10% for a multi-decadal drought. These results were largely insensitive to emissions scenario, likely due the long timescale built into the statistical correction.

Moving now to the hydrologic perspective necessary to assess drought risk in BC, we return to two studies mentioned earlier. First, the change in snowpack susceptibility under future warming was considered by Dierauer et al. (2019). Building on their study of historical data that identified a mean winter temperature threshold for rapid snowpack melt, the authors applied a simple +2°C shift to the threshold to estimate the effect of regional warming on snowpack susceptibility in the Pacific Northwest. In BC, this resulted in a nearly 30% increase in the volume of snow in coastal basins considered to be of medium-to-high susceptibility, and a 10-15% increase in volume of medium susceptibility snowpack in interior basins.

As mentioned earlier in the context of streamflow projections, Shrestha et al. (2021) noted a steep decline in the projected maximum annual snowpack in the warmer coastal/southern basins of BC over the 21st century. The authors examined how the frequency of near-normal (33rd to 67th percentile), below-normal (< 33rd percentile) and above-normal (> 67th percentile) snowpack changed as a function of global warming level. At a GWL of 2.5 ^{o}C, below-normal snowpack (i.e. snow drought) occurred in over 80% of years, and in essentially all years by a GWL of 4.0 ^{o}C, in those coastal/southern basins. The Peace and Athabasca basins further to the northeast evolved more slowly but were still projected to experience an annual snow drought frequency exceeding 70% by the higher GWL. Most snow drought years were also warmer and wetter than average, throughout the province.

Finally, the relationship between snow drought and summer streamflow was studied by Dierauer et al. (2021) in four headwater catchments in BC. Like Shrestha et al., these authors showed that warm snow droughts are projected to become more frequent in the future. Furthermore, the authors found that in snow drought years, summer streamflow drought conditions were also more likely to develop, particularly in southern basins like the Whiteman and Capilano. Since water demand is highest in these more populated southern basins, this suggests a higher likelihood of water scarcity in this part of the province in future decades, under both medium and high emissions pathways. Additionally, the glaciers of Western Canada, most of which are in B.C., are also at risk. A 2015 study using a glacier model driven by global climate projections found that by end-of-century, the volume of glacier ice in the region may shrink by as much as 70% relative to the 2005 amount (Clarke et al., 2015).

2.4.2 Wildfire

Wildfire is a complex hazard that involves a wide array of climatic and non-climatic variables. The fire regime, or the frequency, intensity, and pattern of wildfires in a region, is affected by the climate, fuel (vegetation) characteristics, and ignition sources. The severity and spread of an existing fire are influenced by factors such as landscape/relief, natural and artificial barriers, fuel characteristics, and weather (e.g., wind magnitude and direction). Atmospheric and land surface conditions conducive to fire initiation and spread are often referred to as fire weather. Indices derived from operational products such as the Canadian Forest Fire Weather Index (FWI) System (NRCan, 2023) are used to consider how weather conditions (namely temperature, precipitation, relative humidity, and wind speed) affect fuel dryness and potential fire behaviour. Wildfire may also be influenced by changes in ignition events (such as lightning activity) and changes in fuel, or forest, characteristics, which are not included in this analysis. Lastly, wildfire risk and impacts may be affected by changes in the length of the fire season, which is projected to increase in future climate scenarios (NRCan, 2024).

Figure 22 shows historical BC-wide trends between 1919 and 2021 for various wildfire-relevant climate variables including spring and summer temperature, total precipitation, and climatic moisture deficit (CMD, sum of monthly evaporation minus precipitation) and annual area burned (Parisien et al., 2023). Over much of the 20th century, the area burned by wildfires decreased, a consequence of increasing precipitation in spring and summer in tandem with fire suppression efforts. The trend in CMD was downward over the 20th century (indicating wetter conditions from a larger influence of precipitation over temperature, which both increased) until reversing direction (i.e., drying) in both spring (starting in 2011) and summer (starting in 1999). The drying trend in recent decades may indicate that evaporative demand driven by increased warming has surpassed the effects of increased precipitation on moisture in these seasons. This change in CMD may be one factor behind the dramatic increase in BC wildfire activity in recent years, although the role of climate variability also needs to be examined.

In recent years, BC experienced three record-breaking wildfire seasons in 2017, 2018, and 2023 (Parisien et al., 2023; Figure 22), all of which burned >1 Mha of land. This is remarkable, since between 1919 and 2016, only three wildfire seasons had a burned area greater than 0.5 Mha. A study by Kirchmeier-Young et al. (2019) found that the fire weather conditions that contributed to the severity of the 2017 wildfire were made 2 to 4 times more likely due to anthropogenic climate change, also finding that the area burned was 7 to 11 times larger than that projected without climate change.

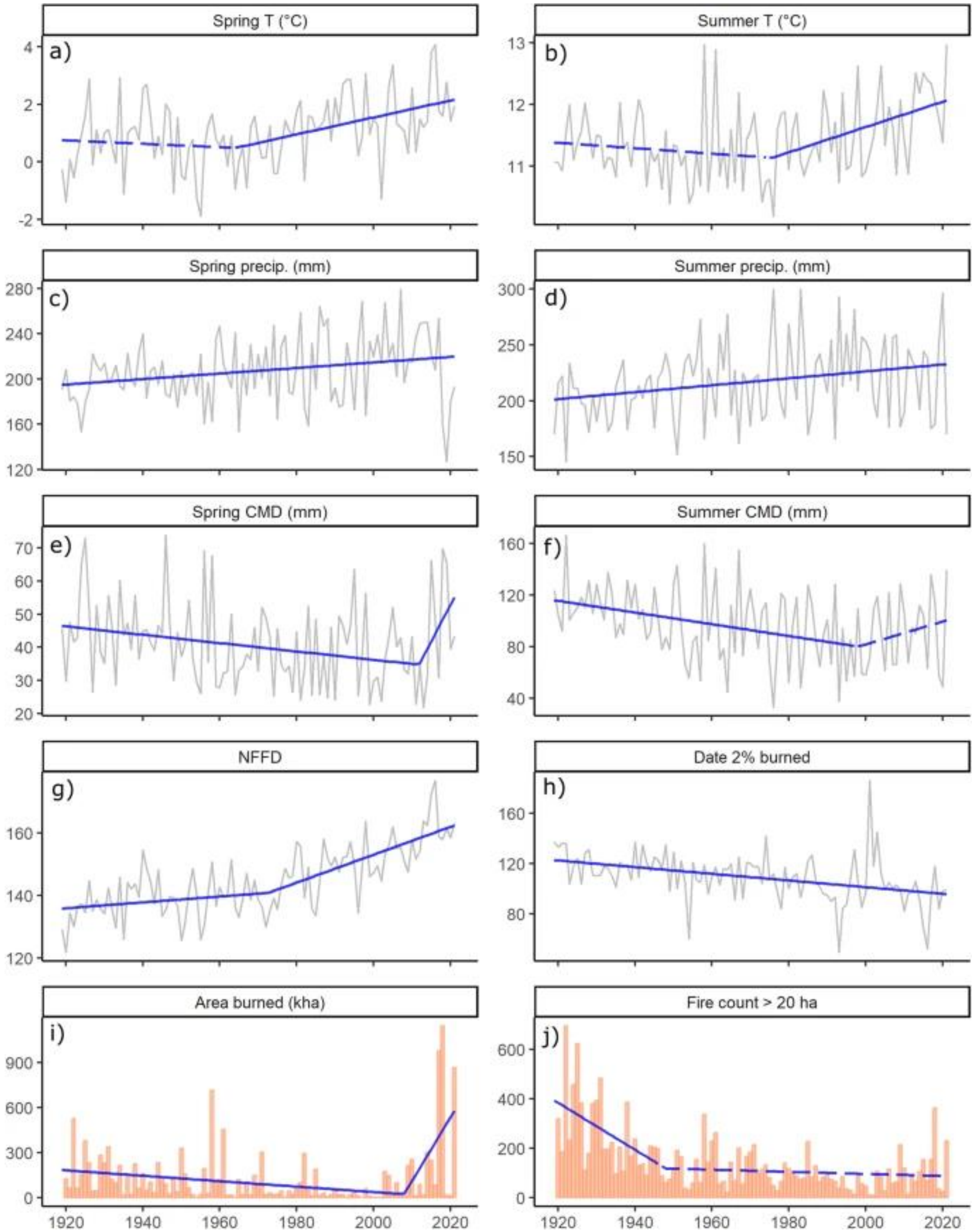

Figure 22. BC-wide trends for spring and summer temperature (a and b), total precipitation (c and d), and climate moisture deficit (CMD; e and f) between 1919 and 2021. Other trends shown are the number of frost-free days (NFFD; g), date of 2% cumulative annual area burned (h), annual area burned (i), and annual number of fires with area > 20 ha (j). Blue lines show segmented regression trendlines while solid lines show significant trends (Parisien et al., 2023).

Turning now to future projections, Parisien et al. (2023) also presented CMIP6 model-simulated temperature and CMD over three areas of BC (Northern, Central, and Coastal) for the remainder of the century (Figure 23). While the median temperature projections in all three regions are similar, projections for CMD are more varied, with the strongest drying trends occurring in Coastal and Central BC. These results suggest that based on temperature trends and moisture deficits alone, these two regions may see the greatest change in wildfire frequency and severity in the future.

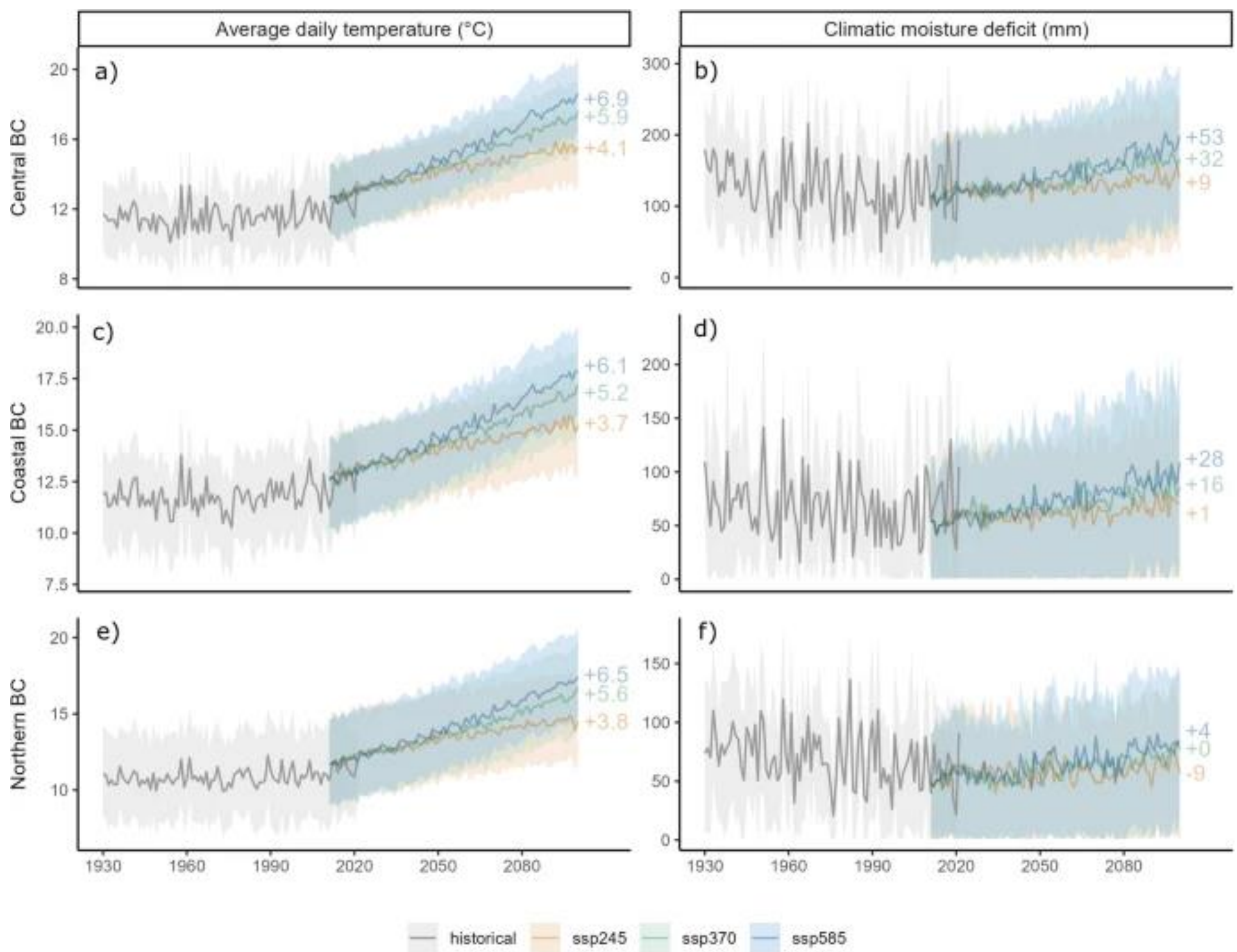

Figure 23. Model-simulated historical and future evolution of average daily temperature (left) and CMD (right) in Central, Coastal, and Northern BC under three emissions scenarios (Parisien et al., 2023).

Projected changes in these climatic drivers are also reflected in the FWI, which provides a general measure of weather-driven fire danger based on relationships derived from observations of forest environments in Canada. One component of the FWI is designed to capture the potential moisture conditions of wildfire fuel on the forest floor. The daily temperature, relative humidity, and rainfall over the preceding days and weeks are used to estimate the cumulative effect of daily weather on fuel dryness. Importantly, FWI increases as drought conditions worsen, and is an open-ended measure with no upper limit. In the context of future climate, this component will reflect the influence of long-term warming trends and meteorological drought, when and where it occurs. The second component of the FWI accounts for wind conditions that affect fire spread, should ignition occur. While this feature is important for short-term fire weather forecasting, it is unlikely to influence median long-term climate projections, where there is often poor agreement amongst models in wind changes at regional scales (Daines et al., 2016). Several studies, using a variety of climate models, suggest an increase in future-projected FWI in BC specifically: see Wang et al. (2015), Wang et al. (2017) and Jain et al. (2020).

We present future projections for FWI recently developed from a large ensemble of bias-corrected Canadian Regional Climate Model simulations (Van Vliet et al., 2024; Cannon et al., 2022), running a high emissions scenario. To probe what might be considered extreme fire weather conditions, we consider the 95th percentile value of FWI, FWIx95, over May to September (central fire season) during the historical reference period (1971-2000).

Figure 24 shows the annual count of days when the FWI exceeds FWIx95 in the historical period compared to two future periods. The figure shows that, averaged over BC, about 11 such days occurred in the past. The number of FWIx95 days increases to 18 at a GWL of 2.5°C (the 2050s under a high emissions scenario, the 2080s under a medium scenario), and to 27 at a GWL of 4.0°C (the 2080s under a high emissions scenario). That is, according to these model projections, extreme fire weather conditions are projected to occur about 2.5 times as often by the end of the century, compared to the 1980s.

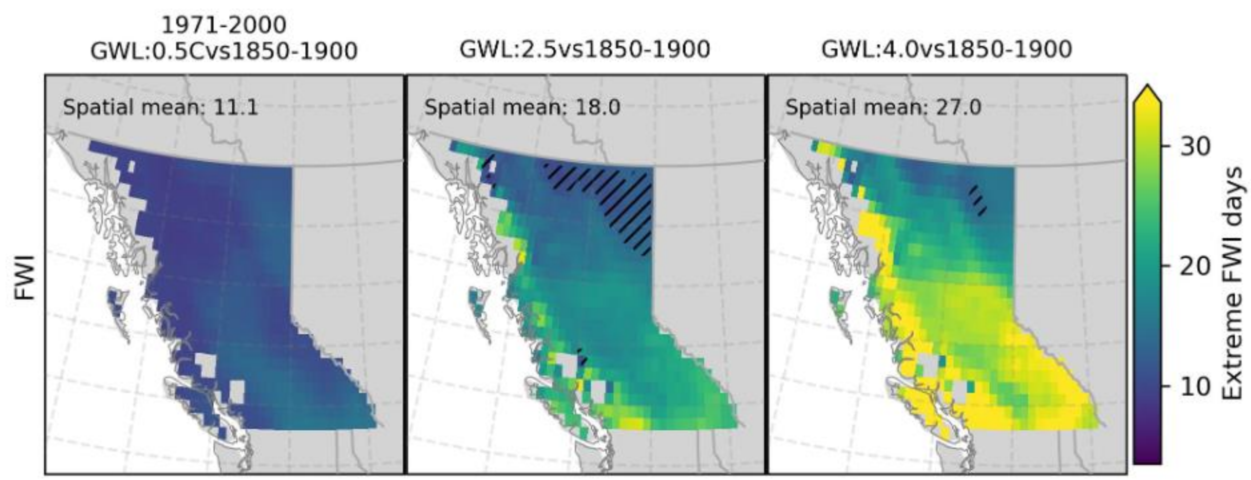

Figure 24. Count of days that exceed the historical 1971-2000 average May to September 95th percentile FWI value, FWIx95, in the historical period (left), at a future GWL of 2.5°C (centre), and at a future GWL of 4.0°C (right). Areas overlaid with hatching in the future period maps are not statistically different from baseline values in the left-hand panel.

2.4.3 Joint riverine and coastal flooding

Joint riverine and coastal flooding is one of the more challenging hazards to assess. The conditions required to provoke such an event are complex and difficult to model as both climatic and geomorphic variables are important, and it involves extremes that rarely interact. However, the interaction between sea level rise or storm surge and high river discharge can result in compound extreme events (Schnorbus and Curry, 2019). It is important to note that for a compound extreme event to occur, it does not necessitate that the two extremes occur simultaneously (Seneviratne et al. 2012). The two events may be successive or not be extreme on their own, rather the combination of multiple events leads to an extreme. To assess risk of a compound event, it is necessary to determine the level of dependence between variables, such as sea level or storm surge and high river discharge (Hao and Singh, 2016; e.g. Klerk et al., 2015; Moftakhari et al., 2017). To our knowledge, this analysis has not been attempted in BC.

For a joint riverine and coastal flooding event to occur the geomorphic conditions must allow for tidal influence on the flow of the feeding river, such as in estuarine systems. Since the Fraser River has a broad floodplain and tide water has been shown to affect salinity, it is possibly a good candidate for an event of this type. However, it is currently uncertain whether floods in the Fraser River are compound events (Schnorbus and Curry, 2019). Under current climatic conditions, peak discharge events are snowmelt-driven and generally not associated with storm surge activity. It is possible that there is some dependence during winter storm events, when storm surge and extreme precipitation occur concurrently. With climate change, the contribution of extreme rainfall to high discharge events is projected to increase, suggesting an increase in the possibility of compound events in the future.

2.4.4 Extreme rainfall and landslides

Extreme rainfall is a main contributing factor to landslide hazards in BC, which have resulted in significant damage to infrastructure and also fatalities. BC is particularly vulnerable to landslides due to its complex topography and geomorphology, and continuous exposure to intense multi-day storms from the Pacific Ocean (Sobie, 2020). Between 1880 and 2019, landslides caused 390 recorded fatalities in BC, with the rate of fatalities decreasing over time (Strouth and McDougall, 2021). However, landslides remain an increasing concern with future climate change. Using an ensemble of downscaled CMIP5 models running a high emissions scenario (RCP8.5), landslide frequency is projected to increase 32% (an increase of 5 days per year) by the 2050s. Increases in landslide frequency are seen in all sub-regions in BC that are currently prone to landslides (Figure 25). The largest increases are seen in coastal areas and in the northern Rockies and Boreal Mountains (+49-61%; +8-11 days/year). Landslide frequency primarily increases in the normally wet fall and winter seasons, which also corresponds to the seasons with the largest projected increases in precipitation due to climate change.

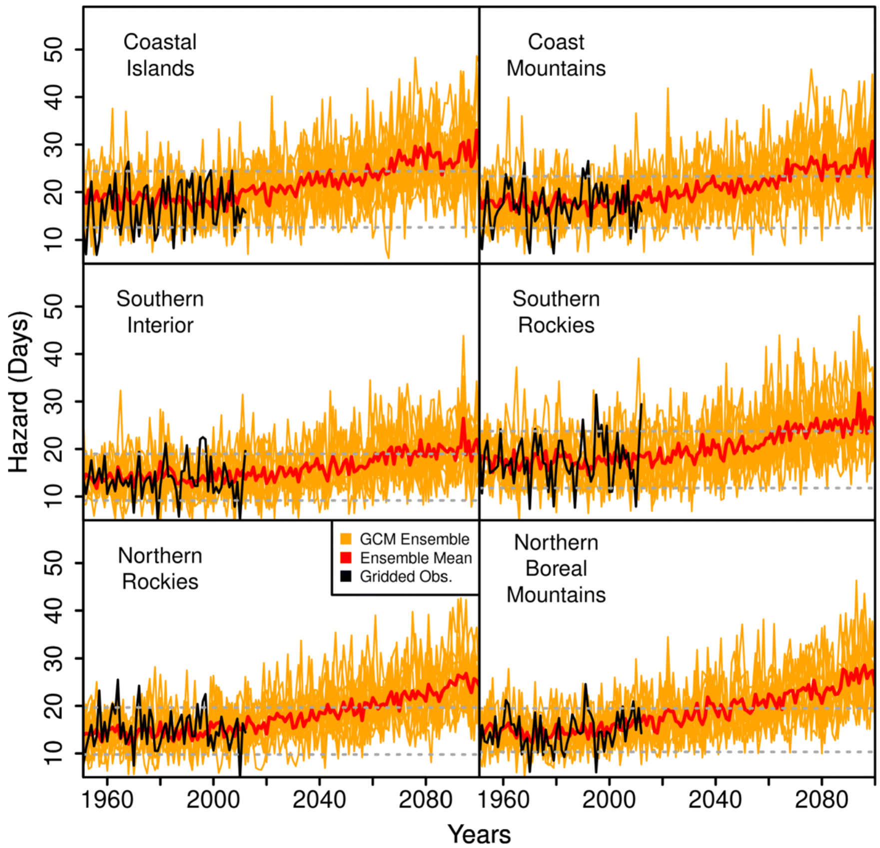

Figure 25. Time series of annual landslide hazard from 1951 to 2100 days for six sub-regions of BC, under the RCP8.5 emissions scenario (Sobie, 2020). Downscaled GCM results are shown in orange and the ensemble mean is shown in red. Historical data from gridded observations is shown in black.

3. Summary and Conclusions

This Annex provides background information for foundational climate science concepts, historical context for BC's climate, and future projections for key climate variables relevant to five climate-related hazards in BC. These hazards comprise extreme heat, drought, wildfire, and riverine and coastal flooding. We refer to climate variables that result in impacts to humans, ecosystems, the built environment, etc., as hazard drivers. The Annex is organized around hazard drivers, providing historical context and future projections for temperature and precipitation, followed by sea level and multi-variable hazards.

Historically, annual average surface temperature has increased in BC and is projected to increase further. However, rising average temperatures does not necessarily constitute a hazard. For this reason, we analyze changes in extreme heat using a measure that has a known impact. We use the BC HARS heat warning thresholds for different regions in BC to determine the magnitude of 3-day heatwaves and assess historical and future-projected occurrences of heatwaves. In the historical period, we find that heatwaves of these magnitudes rarely occur over most of BC. With increasing global temperatures, we find that 3-day events of these magnitudes occur much more frequently, indicating an increase in risk in heat-related impacts.

Annual precipitation is projected to increase in the future. However, increases in precipitation do not necessarily indicate an increase in riverine flooding or decrease in drought. Understanding risk for riverine flooding requires an understanding of the factors affecting streamflow, which vary considerably over BC due to diverse climatic zones and topography. Temperature-driven declines in snowpack are projected to have a stronger influence over snow drought than increases in cold season precipitation, leading to earlier peak snowpack and peak flows in many basins. However, changes in the magnitude of peak flows varied considerably depending on location. For example, peak flow for the Fraser River Basin is primarily snowpack influenced, with peak flows occurring primarily in the late spring-early summer. With projected decreases in snowpack in the future, peak flows are projected to occur earlier and become more heavily influenced by extreme rainfall in the future.

Global mean sea level has risen significantly since 1900 and is projected to further increase in the future. However, sea level could rise even further when including deeply uncertain ice-sheet processes. Since local, or relative sea level is influenced by different processes than the global mean, sea level projections can vary significantly for different regions. However, estimates of relative sea level do not tell us much about coastal flooding alone. It is important to understand how sea level changes relative to typical flood levels for a given region. As with riverine flooding, the factors affecting coastal flooding in BC vary considerably by region. Coastal flooding can occur in the fall and winter, when BC's coast is hit with intense storms that can generate storm surges, and temporarily cause further increases to sea level. For the Fraser River mouth, historical 100-year extreme water-level events during the cold season are projected to occur more frequently by 2050, and much more frequently by 2100. Changes in extreme water level frequency coincide with increases in relative sea level by the end of the century at the Fraser River mouth, indicating an increased risk for coastal flooding events at this location.

Evaluating multi-variable hazards, including drought, wildfire, joint riverine and coastal flooding, and landslides, is especially challenging. This is especially true of joint riverine and coastal flooding due to the need to assess the level of dependence between variables such as sea level rise and high river discharge. The Fraser River provides an example of a location where this type of hazard could occur, although it is uncertain whether historical flooding events on the Fraser had a significant coastal flooding component. The risk of hydrologic drought is significant, given projected increasing temperatures and reduced snowpack. Snow droughts are projected to increase in frequency in the future, which would increase the risk of summer streamflow drought, all things being equal. This is projected to occur in southern BC basins where the water demand is high, thus posing a risk for water scarcity in the future under both moderate and high emissions scenarios. To assess the wildfire hazard over BC, we examined the projected change in the fire weather index, which exhibits a widespread increase in the future. Results from a landslide analysis show the largest increases in landslide hazard frequency are expected to occur in coastal areas and the northern Rockies, again with increases projected in all areas where landslides are a risk historically.

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Disaster and Climate Risk and Resilience Assessment

(DCRRA)

Appendix C:

Technical Case Studies

Table of contents

Introduction to academic case studies

Understanding risk is an ongoing endeavor with continuous need to collect and analyze new data and to improve and revise methodologies, models and projections of future conditions and hazards. As part of efforts to understand and manage risk and resilience, EMCR has provided funding to academic institutions to ensure that cutting edge research can help support fact-based decisions and policies. In this chapter/annex, we share updates on some ongoing research projects that may improve our understanding of risk. The academic case studies were written by experts from B.C. universities, to highlight potential advances in studies of hazards, risk and resilience, with high-level overviews of the importance and potential implications of these ongoing studies. The presented studies were partially supported by EMCR and represent a snapshot in time of work, related to other research that is underway.

Case Study 1: State of disaster and resilience literature in B.C.

Charlotte Milne, University of British Columbia
Taylor Legere, University of British Columbia
Jonathan Eaton, University of British Columbia
Sara Shneiderman, University of British Columbia
Carlos Molina Hutt, University of British Columbia

Introduction

British Columbia is exposed to diverse natural hazards,[1,2,3] leading to extensive research into disaster and resilience topics in the province. However, within disaster studies there is commonly a siloing of research and knowledge between different fields, hindering integrated risk reduction solutions.[4,5,6] To better understand the state of disaster and resilience research in B.C., the authors reviewed available academic literature. Findings reveal the hazards, methodologies, disciplines, events, and B.C. locations referenced in the literature, providing context for future innovative research and response efforts.

Methodology

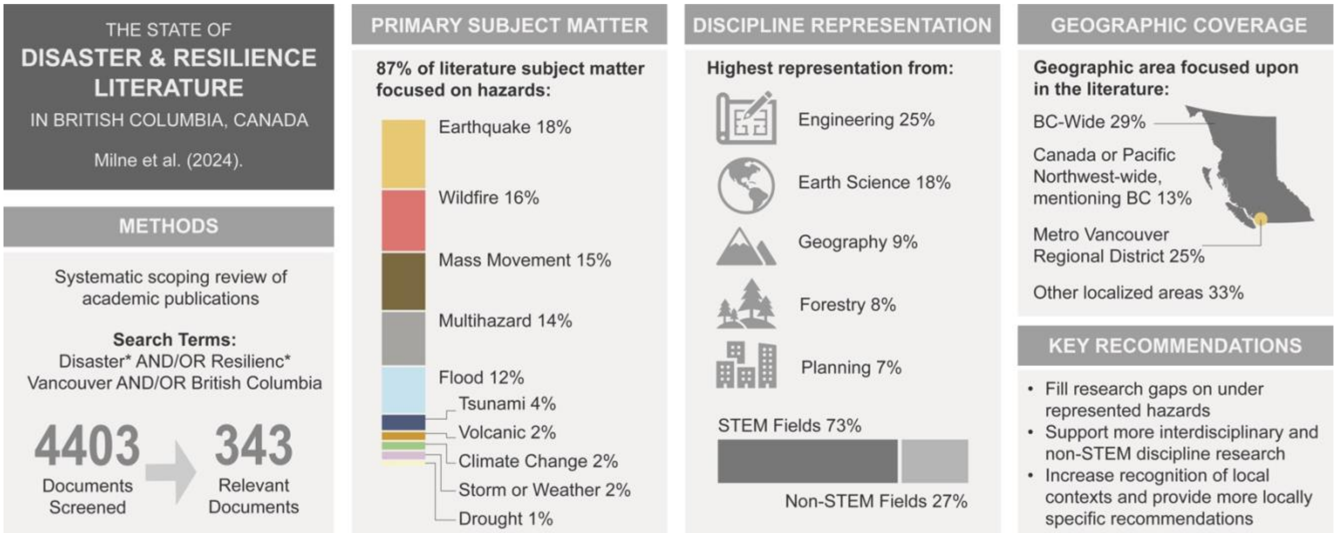
The authors undertook a systematic scoping approach to allow for an interdisciplinary, geographically bounded examination of the literature. Twenty-four databases were systematically searched, with additional records added from Google Scholar and researcher recommendations. The authors screened 4,403 records, of which 343 documents were analyzed in full. Further details about the methodology can be found in the published paper on this work.[7]

Search terms were chosen to capture breadth within the field[8], allowing specific topics discussed in the context of "disaster" and "resilience" in B.C. to be revealed. Initial testing[9] led to the use of: {"British Columbia" AND/OR Vancouver} AND {Disaster* AND/OR Resilience*}. Documents were read and classified based on publication details, main topics, hazard types, hazard events, geographic area, and other details. Results were compared with the Canadian Disaster Database to assess how the literature compared to B.C.'s historic disaster trends.

Findings / Learnings

HIGHLIGHTS	DETAILS
Natural hazards were the primary subject matter for 87% of documents, while 13% discussed disaster and resilience more generally.	Earthquakes were the most frequently discussed hazard, despite floods being the most frequent disaster-causing hazard in B.C. over the last century. Storm/extreme weather and drought were the least discussed hazards. 14% of the documents discussed multiple hazards, with flood and mass movement most often discussed together.
Science, technology, engineering, and math disciplines published the most on the reviewed themes (73% of documents).	Approximately half of the documents reviewed deployed quantitative research methods, 20% utilized qualitative research, 20% descriptive methods, and the rest were based on review, opinion or mixed methods.
A spatial disconnection was found between locations discussed in the literature versus historical disaster trends.	Less than half of the literature discussed B.C. disaster or resilience at broad scales, with 29% classified as B.C.-wide, 13% classified as Canada-wide or Pacific Northwest–wide, and the remaining 58% were classified as within the boundaries of regional districts, with a notable concentration in Metro Vancouver (25%).

Figure 1: Graphic Abstract, The State of Disaster and Resilience Literature in British Columbia, Canada. Milne et al. (2024).



Recommended future research to improve risk understanding

1. **Expand disaster resilience research into under-represented hazards**, such as drought or extreme weather, including additional discussion of hazards within multi-hazard contexts and interdisciplinary approaches.
2. **Support and engage with Indigenous-led research**, and if appropriate and requested, seek out opportunities for co-designed and collaborative academic research. This will help ensure First Nations' Knowledge and priorities are included in understandings of disaster and resilience in BC.
3. **Consider grey literature and other knowledge sources** for how they might fill the gaps identified in this review.

Resources

Charlotte Milne et al., "The State of Disaster and Resilience Literature in British Columbia, Canada. A Systematic Scoping Review," manuscript in review, preprint available through SSRN, accessed June 2, 2024. https://doi.org/10.1016/j.ijdrr.2024.104848

Disaster Resilience Research Network, "BC Disaster & Resilience Literature Review," University of British Columbia, accessed June 6, 2024. https://drrn.ubc.ca/bc-disaster-resilience-literature-review

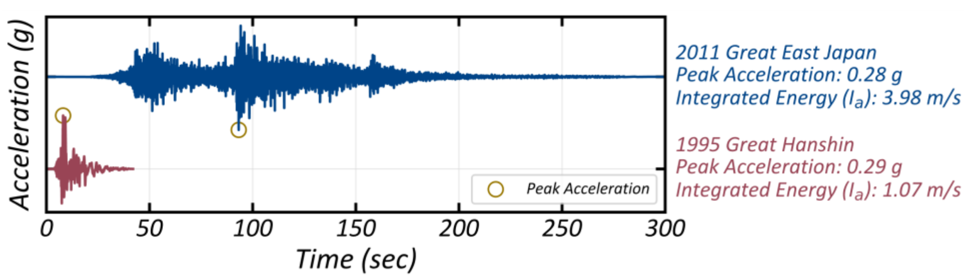
Case Study 2: Advancing the understanding of liquefaction from multiple seismic sources in British Columbia

T.J. Carey, University of Toronto
Y. Keshty, Fugro West Inc.

Introduction

Liquefaction, the loss of strength and stiffness of saturated soil due to ground shaking, is a significant risk factor for infrastructure and buildings constructed on soil and loose sediments in the lower mainland and other locations in B.C. During a large-magnitude (M=8-9.1) Cascadia Subduction Zone earthquake, long duration of shaking may increase the risk of liquefaction and ground deformations. As earthquake magnitude increases, so does the duration of shaking and the number of stress-loading cycles experienced by soils and structures. During the 2011 Great East Japan (M=9.1), the shaking lasted nearly five minutes; in contrast, the 1995 Great Hanshin earthquake (M=6.9) was 40 seconds in duration (Figure 2). These magnitude effects are accounted for in the liquefaction analysis procedures, but the engineering community's knowledge base for liquefaction was primarily developed using case history data from lower-magnitude earthquakes because they occur more frequently. The current analysis procedures are being extended to Cascadia Subduction Zone earthquakes, which is beyond their original scope.

Figure 2: Comparison of earthquake records from the 2011 Great East Japan and 1995 Great Hanshin earthquakes.



Methodology

Addressing this challenge involves using recently published global ground motion databases and analytical procedures to determine the number of loading cycles from earthquakes. We compare study findings with existing known quantities of loading cycles for lower earthquake magnitudes published in liquefaction procedures. To test the robustness of current procedures and accurately account for all seismic sources in British Columbia, ground motions from lower magnitude subduction zone events and crustal earthquakes, like those from California, are considered. By harnessing machine learning tools, analysis trends are identified to better evaluate which aspects of earthquakes are most likely to influence the number of loading cycles. This approach ensures accurate assessment of liquefaction potential from the Cascadia Subduction Zone earthquake and other regional seismic hazards in British Columbia.

Findings / Learnings

Current liquefaction analysis procedures are inaccurate in predicting the number of loading cycles from large magnitude earthquakes. Furthermore, the complex seismic source conditions in British Columbia are not adequately modelled using current procedures.

HIGHLIGHTS	**DETAILS**
Earthquake magnitude alone is a poor predictor of the number of loading cycles contained in an earthquake record	Following conventional procedures, an engineer only needs to know the earthquake magnitude to predict the number of loading cycles. However, our analysis of the 2011 Great East Japan earthquake showed that earthquake motions with high intensities that could produce soil liquefaction might have as few as five to as many as 100 loading cycles.
Earthquake magnitude procedures are dependent on earthquake type	Our analysis found that current procedures could not accurately predict the number of loading cycles from intraplate earthquakes and produced a significantly larger number of loading cycles compared to conventional California-type crustal and subduction zone interplate earthquakes. This would suggest the need to account for earthquake source type in predicting the number of loading cycles and the effect of liquefaction.
Earthquakes with large magnitude exhibit greater variability compared to lower magnitude events	Analysis of larger-magnitude events challenges the underlying assumptions of currently used liquefaction analysis procedures.

1. Recommended future research to improve risk understanding. Improved liquefaction analysis is needed to improve risk assessment and preparedness for a Cascadia earthquake. Future, improved, liquefaction analyses should account for the complex earthquake sources in British Columbia.
2. Research results such as liquefaction data and models should be made available to engineering practitioners in an easy-to-use or implementable format (i.e., simplified design equations, or spreadsheet solutions).

Resources

Natural Resources Canada (NRCan), "Questions and Answers on Megathrust Earthquakes," accessed May 2024. https://www.earthquakescanada.nrcan.gc.ca/zones/cascadia/qa-en.php

Pacific Northwest Seismic Network (PNSN), "Liquefaction," accessed May 2024. https://pnsn.org/outreach/earthquakehazards/liquifaction

U.S. Geological Survey, "What is liquefaction?," accessed May 2024. https://www.usgs.gov/faqs/what-liquefaction

Case Study 3: Deep sedimentary basin amplification of earthquake ground motions

Preetish Kakoty, University of British Columbia
Carlos Molina Hutt, University of British Columbia

Introduction

Southwest B.C. has the potential to experience large-magnitude earthquakes generated by the Cascadia Subduction Zone (CSZ). Buildings in Metro Vancouver are particularly vulnerable to these earthquakes because the region lies above the Georgia Sedimentary Basin, a geological depression or low-lying area where sediments accumulate over time.

From past earthquake recordings, sedimentary basins have been shown to amplify ground motion shaking, particularly at long periods, impacting tall buildings and other long-period structures.[10,11] Historically, deep basin amplification effects have not been explicitly accounted for in national seismic hazard models, and thereby not accounted for in building codes. However, in recent years, the amplification effects of deep sedimentary basins on long-period earthquake ground motions have been more closely studied. For the first time, the United States Geological Survey included basin effects in the 2018 version of the US National Seismic Hazard Model and, as a result, basin effects are now included in US building codes. While progress has been made in the US, Canada's 6th Generation Seismic Hazard Model[12] and the National Building Code of Canada (2020)[13] do not explicitly account for these effects. This highlights a critical gap in our understanding of the seismic hazard in the region, especially Metro Vancouver as it sits above the Georgia Sedimentary Basin.

This case study leverages a suite of physics-based ground motion simulations of M9 CSZ earthquakes to quantify the amplification effects of the Georgia Sedimentary Basin, and also to develop site-specific basin-amplification factors that can be applied to existing seismic hazard estimates in Southwest BC to enable explicit consideration of these effects in the design of new and assessment of existing buildings and infrastructure.

Methodology

Due to the paucity of recorded ground motions from the CSZ, a group of researchers from the United States Geological Survey and the University of Washington simulated 30 scenarios of an M9 earthquake originating on this fault and generated ground motion records for the entire Pacific Northwest region.[14] These simulations explicitly consider basin effects by utilizing a 3D velocity model[15] of the region that characterizes the subsurface geology. This study explores basin amplification effects in the Metro Vancouver region by benchmarking seismic hazard estimates from the simulated ground motions against Canada's national seismic hazard model, which does not consider basin effects.

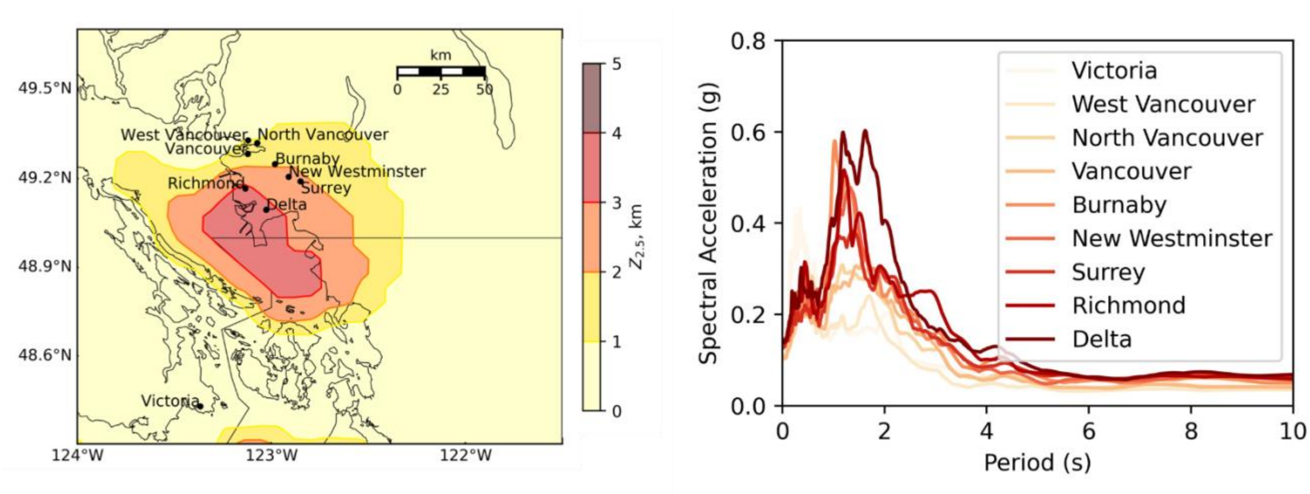
A framework has been developed to quantify basin amplification factors for a range of sites within Metro Vancouver that lie on the Georgia Sedimentary Basin with respect to sites located outside the basin (Figure 3. The basin amplification factors consider uncertainties due to variations in rupture properties, ground motion model estimates, and azimuthal variations of reference site conditions. These basin amplification factors are site specific and period dependent. A framework is also proposed to incorporate these factors into the Uniform Hazard Spectra (UHS) that inform building design to integrate basin amplification effects into the design process until these effects are explicitly accounted for within the national seismic hazard model.

Findings / Learnings

HIGHLIGHTS	DETAILS
Basin amplification varies spatially across sites within Metro Vancouver and generally correlates well with basin depth.	Basin amplification varies spatially across sites within Metro Vancouver. These effects generally correlate well with $Z_{2.5}$, a commonly used proxy for basin depth, which denotes the depth to soils with a shear wave velocity of 2.5 km/s. For instance, the average basin amplification factor for Metro Vancouver locations with $Z_{2.5}$ in the 1–2 km range is 1.7 at a 2 s period, and it is 2.63 at the same period for sites with $Z_{2.5}$ in the range of 3–4 km.
Basin amplification results in higher seismic design ground motions, highlighting the need to increase the design parameters used	When basin amplification effects are integrated into the calculation of Uniform Hazard Spectra (UHS), a design tool used to

in the National Building Code of Canada for basin locations.	characterize earthquake ground motions, this results in higher seismic design forces, particularly for taller buildings (with periods of vibration of 1–3 s). For instance, at a site in the City of Vancouver (49.24, -123.11), when the UHS is modified to account for basin effects, it is 24% higher at a 2 s period when compared to the UHS that neglects such effects.

Figure 3: Contour of Georgia basin depth in terms of $Z_{2.5}$ (depth to deposits with shear wave velocities of 2.5 km/s), with warmer colors indicating greater basin depth (left), and ground motion spectra acceleration from one plausible M9 Cascadia Subduction Zone earthquake scenario at a range of sites within Metro Vancouver and Victoria (right). Spectral acceleration is a measure of ground motion that takes into account the sustained shaking energy at a particular period. The sites are listed in increasing order of basin depth. Higher ground motion shaking intensity is observed at sites with higher $Z_{2.5}$.



Recommended future research to improve risk understanding

1. **Complete ongoing studies:** The ongoing Metro Vancouver Seismic Microzonation Project[16] will further characterize the properties of the Georgia Sedimentary Basin and its potential ground motion amplification effects.
2. **More comprehensive and advanced research** and analysis is needed to rigorously characterize basin amplification effects to enable their inclusion in regional seismic hazard estimates. While the 3D basin model used in the simulations characterizes the subsurface properties at higher depths (up to 60 km) appropriately, it has limitations in

characterizing the top layers of soil (top 30 m). Appropriate considerations of the geotechnical layer in the Georgia Sedimentary Basin are needed, particularly in soft soil sites (e.g., Richmond, Delta) as this could lead to further amplification of ground motion shaking.

3. **Integrate basin effects in risk assessment studies:** Risk studies should attempt to account for basin effects in order to more accurately characterize the hazard and consequently provide a better understanding of seismic risk in the region.

Resources

Preetish Kakoty, Sai Mithra Dyaga, and Carlos Molina Hutt, "Impacts of simulated M9 Cascadia Subduction Zone earthquakes considering amplifications due to the Georgia sedimentary basin on reinforced concrete shear wall buildings," Earthquake Engineering & Structural Dynamics 50, no. 1 (January 2021): 237-256. https://doi.org/10.1002/eqe.3361

Preetish Kakoty et al., "Spectral acceleration basin amplification factors for interface Cascadia Subduction Zone earthquakes in Canada’s 2020 national seismic hazard model," Earthquake Spectra 39, no. 2 (May 2023): 1166-1188. https://doi.org/10.1177/87552930231168659

Preetish Kakoty, "Basin amplification effects and seismic performance of non-ductile reinforced concrete shear wall buildings during subduction earthquakes," (PhD diss., University of British Columbia, 2024). http://hdl.handle.net/2429/87278

Case Study 4: Seismic resilience of B.C.'s hospital infrastructure

Kiranjot Kaur, University of British Columbia
Carlos Molina Hutt, University of British Columbia
Sam Orr, Vancouver Coastal Health
Tim White, Bush, Bohlman & Partners

Introduction

Earthquake activity in the Cascadia region poses a significant threat to populations and infrastructure throughout the province of B.C. For instance, the Cascadia subduction interface fault, off the west coast of Vancouver Island, has the capacity of producing M9 earthquakes with an estimated probability of occurrence of 14% in the next 50 years.[17]

Healthcare facilities throughout the province, and especially in the Lower Mainland, are relied upon in case of emergency to provide continuous services to regional populations. However, much of the hospital infrastructure in the province was constructed prior to the development of modern design standards and without adequate provisions for seismic design to address the earthquake hazard.

The purpose of this study is to assess the expected seismic performance of hospital buildings under a range of earthquake ground motion intensities.

Methodology

The British Columbia Health Seismic Database (BCHSD), developed and maintained by Bush, Bohlman & Partners, and facility condition assessment reports from Vancouver Coastal Health (VCH) are used to provide data needed to perform the assessment.

Results of an assessment for a portfolio of buildings within VCH's jurisdiction are presented at three ground motion shaking intensities with probabilities of exceedance of 2%, 5%, and 10% in 50 years, which correspond to return periods of 2475, 975 and 475 years, respectively. The analysis was performed using seismic hazard estimates from the National Building Code of Canada (2020) using the online calculator,[18] based on site location and soil site class information from BCHSD. These shaking intensities ranged from a spectral acceleration of 0.09g to 1.32g at periods of 0.3, 0.6 and 1 second.

Fragility functions, drawn from Canada's first public, national seismic risk model developed by Natural Resources Canada,[19] were used to characterize the seismic performance of buildings. Fragility functions are provided for building classes defined by predominant construction material, lateral force resisting system, building height, and code era. These functions describe the probability of experiencing different damage states as a function of ground motion shaking intensity.

Findings / Learnings

HIGHLIGHTS	DETAILS
Building-level information for VCH buildings was accessed from the BCHSD.	Although the BCHSD has information about select buildings in VCH, Fraser Health, Providence Health Care, and Provincial Health Services Authority, only data from VCH was used as part of this case study since we are partnered with VCH for this work. However, the findings are applicable to other health authorities in the province.
Around 65% of VCH buildings (pre-code and low-code buildings) are likely to experience complete damage due to shaking corresponding to the design ground motion currently used in the 2020 National Building Code of Canada.[20]	The construction year of hospital buildings was used as a proxy for expected seismic performance. Buildings constructed prior to 1970 are considered pre-code, from 1970 to 1991 are considered here as low-code, from 1992 to 2005 are considered moderate-code, and anything constructed after 2006 is high-code.[21] From VCH's 127 buildings, 32 are pre-code, 51 are low-code, 27 are moderate-code, and 17 are high-code (Figure 4).
If VCH buildings were to experience current design ground motion intensities, the majority of buildings would experience damage that would compromise hospital functionality.	For the three hazard intensity levels considered (2%, 5%, and 10% in 50 years), "complete" damage is expected for 66%, 57%, and 51% of buildings, respectively (Figure 5).

Figure 4: Distribution of the VCH buildings considered in this study by seismic code area.

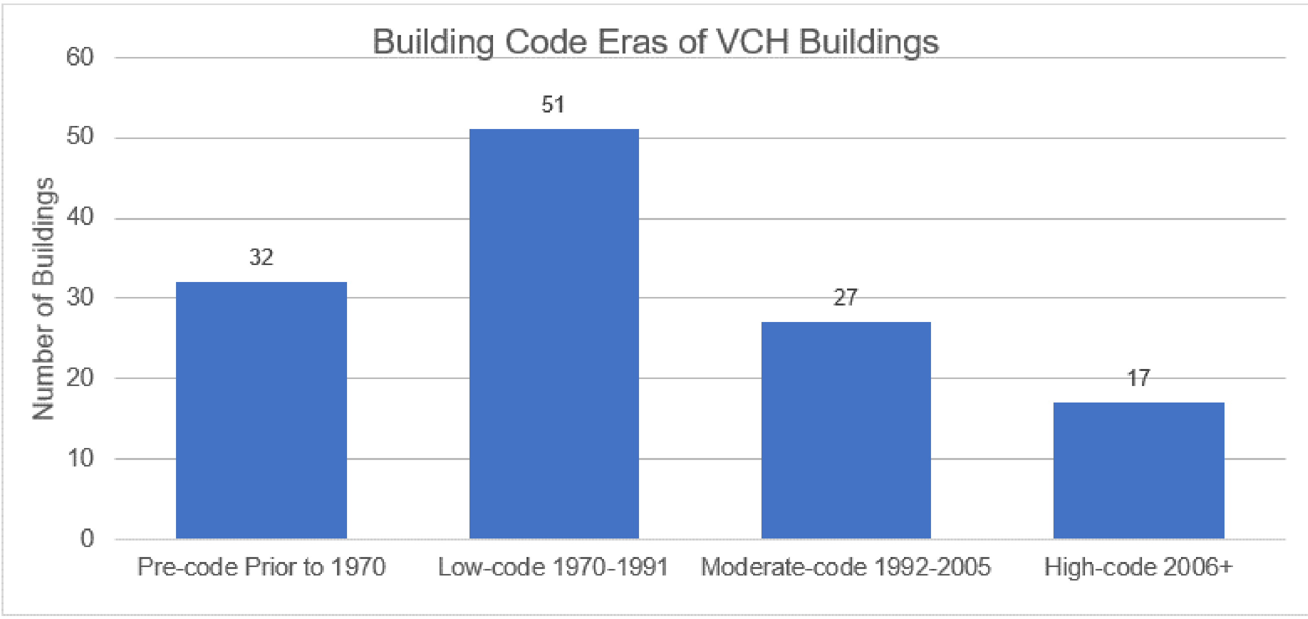
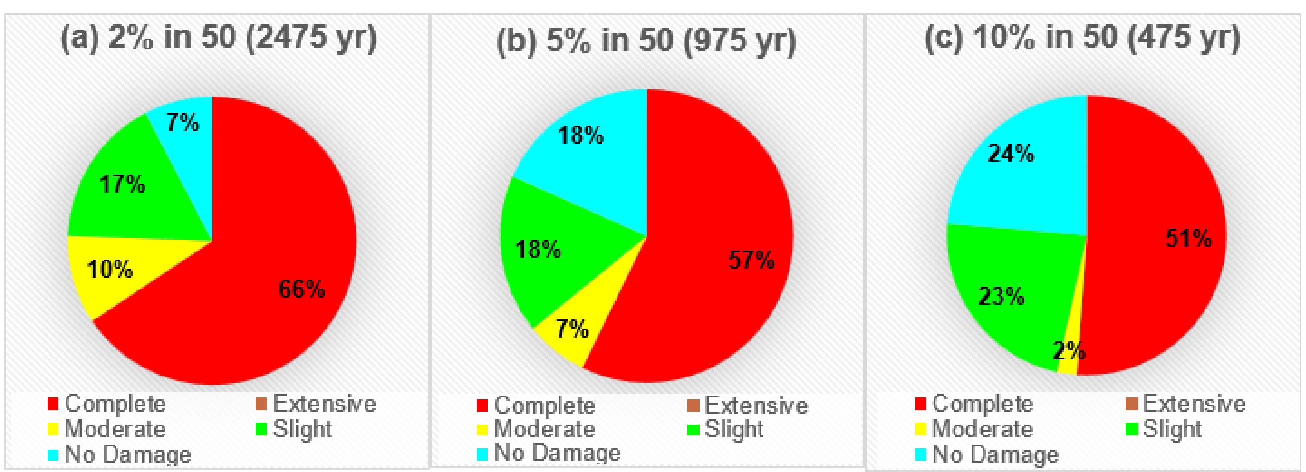


Figure 5: Distribution of most probable damage state for buildings in VCH under three ground motion shaking (seismic hazard) intensity levels with probabilities of exceedance of (a) 2%, (b) 5% and (c) 10% in 50 years.



Recommended future research to improve risk understanding

Expand seismic performance assessments to all hospital buildings in the province, similar to that presented in this case study, to gain insights into their expected seismic performance.

More reliable seismic performance assessment results can be obtained by means of detailed engineering assessments on a building-by-building basis.

Resources

Gerald Palomino Romani, Kristen Blowes, and Carlos Molina Hutt, "Evaluating Post-Earthquake Functionality and Surge Capacity of Hospital Emergency Departments Using Discrete Event Simulation," Earthquake Spectra 39, no. 1 (February 1, 2023): 402–33. https://doi.org/10.1177/87552930221128607

Kristen Blowes, Gerald Palomino Romani, and Carlos Molina Hutt, "Using Discrete Event Simulation to Evaluate the Post-earthquake Surge Capacity in Hospital Emergency Departments," Proceedings of the 12th National Conference in Earthquake Engineering, Earthquake Engineering Research Institute, Salt Lake City, UT, 2022. http://dx.doi.org/10.14288/1.0435905

Carlos Molina Hutt, "Seismic Design of Buildings for Functional Recovery," in Resilient Pathways Report: Co-creating New Knowledge for Understanding Risk and Resilience in BC, eds. S. Safaie, S. Johnstone, N.L. Hastings (Vancouver: Geological Survey of Canada, Open File 8910, 2022): 241-256. https://doi.org/10.4095/330537

Case Study 5: High-consequence rapid movement of landslides

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Dwayne Tannant, University of British Columbia Okanagan

About the project

Rapidly moving landslides that enter water bodies pose a cascading sequence of hazards to people, infrastructure, and the environment throughout B.C. In preparing for the next earthquake, it is important to recognize that landslides may account for a significant portion of the damage arising from shallow inland earthquakes. A major problem in interpreting slope movements for known landslides is predicting future slope behaviour and establishing conditions that create a transition to possible catastrophic rapid failure, with or without an earthquake. This research project will integrate insights from literature review and field mapping, with advanced numerical modeling of the Dutchman's Ridge landslide and the risk that such landslides inflict in B.C.

Introduction

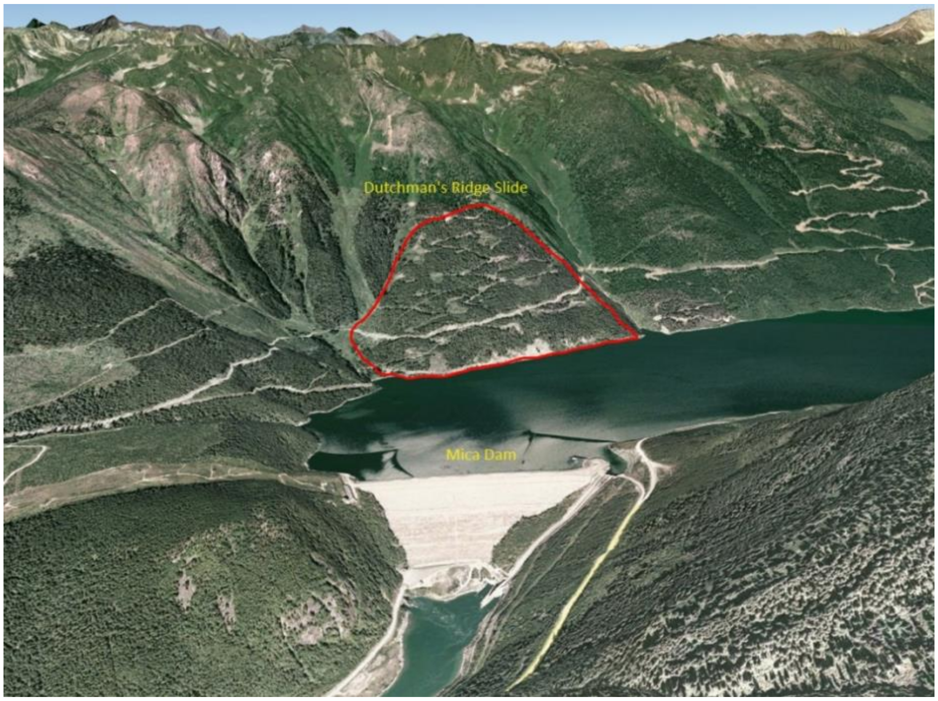
Landslides are common throughout British Columbia, and some can move quickly with little or no warning. Fast-moving landslides that run into rivers or lakes can create a cascade of hazard events extending much farther than the landslide footprint. A recent example is the 2024 landslide that completely blocked the Chilcotin River. The landslide dam eventually breached and released a huge pulse of water and debris downstream that caused extensive erosion along the Chilcotin River. This event also triggered hundreds of smaller landslides and affected salmon migration. The Stó:lō Syélt Xésxel Fraser River Debris Trap facility recently experienced significant media and other attention[22,23] due to the successful mitigation and capture of debris[24] from the Chilcotin River landslide. Earthquakes can trigger fast-moving landslides, such as the 1946 Mount Colonel Foster rockslide[25] on Vancouver Island, which generated a wave with a 51 m high run-up in a lake. However, other poorly understood conditions can trigger fast-moving landslides, such as the 2007 rockslide that generated a wave in Chehalis Lake[26] east of Vancouver with a run-up height of 38 m, the Gar Creek landslide[27], which killed four people at Johnson Landing on Kootenay Lake in 2012, and the 2020 Elliot Creek rockslide[28] that generated a 100 m wave run-up, extensive erosion, and loss of salmon spawning habitat along a river flowing into Bute Inlet. Multiple landslides have entered Harrison Lake[29] in pre-historic times, and there is concern for further landslides.

Landslides much larger than those mentioned above exist along the Columbia River Valley behind BC Hydro's Revelstoke and Mica dams[30]. These include the Downie, Checkerboard Creek, Dutchman's Ridge, Little Chief, and the recently discovered St. Cyr landslides. These BC Hydro dams generate approximately half of BC Hydro's power. The landslides are slow-moving but could accelerate into the reservoir and generate waves that could overtop the dams. Because the landslides are huge, landslide-generated waves[31] higher than anything documented in B.C. could occur. The situation could be similar to the 1963 landslide behind the Vajont dam in Italy[32], which created a large wave that killed over 2000 people in less than 15 minutes.

British Columbia is also exposed to hazards from landslides that enter the ocean and create waves. For example, a landslide in 1953 at Mount Fairweather on the southeast coast of Alaska generated an incredible 524 m high wave run-up[33].

Ongoing research seeks to understand the conditions conducive to rapid landslide movements. Additional research is focused on the potential for a selected landslide (Dutchman's Ridge) behind the Mica dam to create a wave in the reservoir. Advanced numerical modelling is used to evaluate the shear-dependent loss of strength within the landslide materials. The findings are vital to better understand landslide mobility and manage the risks associated with this class of landslides.

Photo: Dutchman's Ridge Landslide near the Mica Dam. 2024 (GoogleEarth).



Findings / Learnings

HIGHLIGHTS	DETAILS
Many landslides have created waves in British Columbia	Landslide sizes vary by many orders of magnitude. Landslides occur in all areas of the province and all geological conditions. Climate change is increasing the likelihood of landslides. Waves can travel long distances and thus greatly extend the hazard beyond the immediate area of the landslide.
A literature review of large rapid landslides in metamorphic rock types was completed specifically for the Columbia River landslides, which occur in metamorphic rocks.	Deep-seated rockslides in foliated metamorphic rock masses are characterized by significant internal fracturing and distortion. Rapid failure occurs more commonly in slopes with multiple shear zones, and earthquakes are a common trigger.
Dutchman's Ridge landslide (115 million m^3) is only 1.2 km from the Mica dam, the highest dam in Canada, which impounds the second-largest reservoir in BC.	When the reservoir was first filled, slope movements were 25 mm/yr. Slope drainage reduced movements to 0.5 mm/yr. The slope movement is primarily driven by seasonal groundwater fluctuations.

Recommended future research to improve risk understanding

1. Better mapping of landslides and the creation of an interactive, continuously updated province-wide landslide map are needed. The mapping must include zones impacted by potential long-runout distances and landslide-generated waves.
2. Further research is needed to recognize and include the potential impacts of climate change, collect evidence of past landslides and include the potential cascading hazards a landslide can generate, such as wave generation.
3. Research is needed to recognize where landslides can occur and the consequences if they happen, including simulations of landslide movements and potential interactions with water bodies. This would help identify and prioritize landslides that should be monitored.

Case Study 6: Machine learning for flood prediction in ungauged basins

Steven Weijs, University of British Columbia

Introduction

Flood risk is a large contributor to total risk from hazards in B.C., and is particularly a major contributor to economic loss. The risk is expected to increase over time due an increase in probability of extreme weather events, such as the flooding in November 2021 as a result of an atmospheric river event. Flood prediction and forecasting can reduce risks by informing rightsholders and partners in a timely manner so that exposure can be reduced.

While flood prediction is routinely done for a large number of gauged locations where measurements of water levels and derived streamflows are available, there are many at-risk locations where no gauge exists. For those ungauged sites, prediction models cannot be calibrated with local flow data.

Methodology

In this study,[34,35] we aim to assess the potential for machine learning to transfer information from gauged catchments to ungauged catchments to expand flood prediction capabilities. The catchment is the land area upstream of a point of interest and its characteristics influence its hydrological behaviour (e.g., how rainfall and snowmelt are contributing to river flows). By feeding catchment characteristics, meteorological data, and streamflow data (inputs) for a large number of gauged sites into a large Long-Short Term Memory neural network, patterns can be discovered that link catchment characteristics to the responding changes to how the water reacts on the landscape, or hydrological functioning (outputs).[36]

The model is evaluated on extrapolation of hydrological behaviour in time. To simulate prediction performance in ungauged catchments, half the gauged catchments was used for training, while the other half was used for testing performance of predictions for a different time period. This setup amounts to extrapolation of behaviour in space and time simultaneously.

Findings / Learnings

HIGHLIGHTS	DETAILS
Database with over 1 million ungauged catchments in and around BC was prepared.	The database contains quantitative geographical details of the catchments, such as location, shape, average elevation and slope, land use, and climate characteristics estimated from remote sensing data averaged over each catchment area. This database will serve for monitoring network design and as input for machine learning predictions.
Machine learning was applied to compare predictions in gauged and ungauged basins.	Reasonable prediction quality was achieved in initial tests on gauged basins with nine years of data used; prediction quality was lower, but still reasonable.

Flooding in the Fraser Valley, BC, after the November 2021 atmospheric river event (Steven Weijs).

Recommended future research to improve risk understanding

1. **Document current forecast quality:** Documenting the accuracy of historic archived weather and river streamflow forecasts at several gauged locations for various lead-times can importantly benefit research and operations.

2. **Simulate ungauged forecasts for comparison:** Set up an experimental forecasting system that produces real-time forecasts for various gauged sites without using local streamflow data and archive forecasts.
3. **Investigate how people use forecast information:** Engage with local communities at risk from flooding to understand what decisions can be made and how warning lead-time and uncertainty play a role in resilience.

Resources

Jonathan M. Frame et al., "Deep learning rainfall–runoff predictions of extreme events," Hydrol. Earth Syst. Sci., 26 (2022): 3377–3392. https://doi.org/10.5194/hess-26-3377-2022

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Case Study 7: B.C. local government actions to address coastal floods

Mauricio Carvallo Aceves, University of British Columbia

Stephanie E. Chang, University of British Columbia

Introduction

This case study provides a systematic overview of actions that local governments in B.C. are taking to address the risk of coastal floods. Actions such as land-use planning or flood construction standards are important for reducing flood risk and enhancing resilience, yet no systematic assessment has been conducted on their current status. Information is needed on the degree to which local governments are already planning, adapting, and taking action; the kinds of actions being undertaken; and differences or disparities across coastal communities. Such a baseline assessment is also important for tracking progress in coastal adaptation over time.

Methodology

This case study provides such a baseline by analyzing data in the Resilient Coasts Canada (Resilient-C)[1] online platform developed at the University of British Columbia. It focuses on communities (municipalities, towns, etc.) as the unit of analysis. Resilient-C contains information on 182 coastal communities across the country. Each community has a profile page in the platform that lists documented actions it is undertaking to address various coastal hazards. For B.C., the Resilient-C platform includes information on 57 coastal communities and some 808 distinct actions they are undertaking to adapt to and address coastal floods.

The Resilient-C data on local government actions have been collected from official community plans (OCPs) and supplemented by other sources, such as hazard risk and vulnerability assessments (HRVAs) and climate change action plans. All data sources are publicly available, current as of 2021, and linked on the Resilient-C platform. From these sources, descriptions of specific actions were identified and systematically marked following an actions collection guide developed by the research team. Data pertain to the types of actions being undertaken

[1] See the Resilient Coasts Canada (Resilient-C) platform: resilient-c.ubc.ca.

(land-use regulations, construction guidelines, damage mitigation, technical studies, emergency preparedness, capacity building, financing and insurance, and other policy and planning work), strategies (protect, accommodate, retreat, avoid), and action stage (groundwork or implementation).

Findings / Learnings

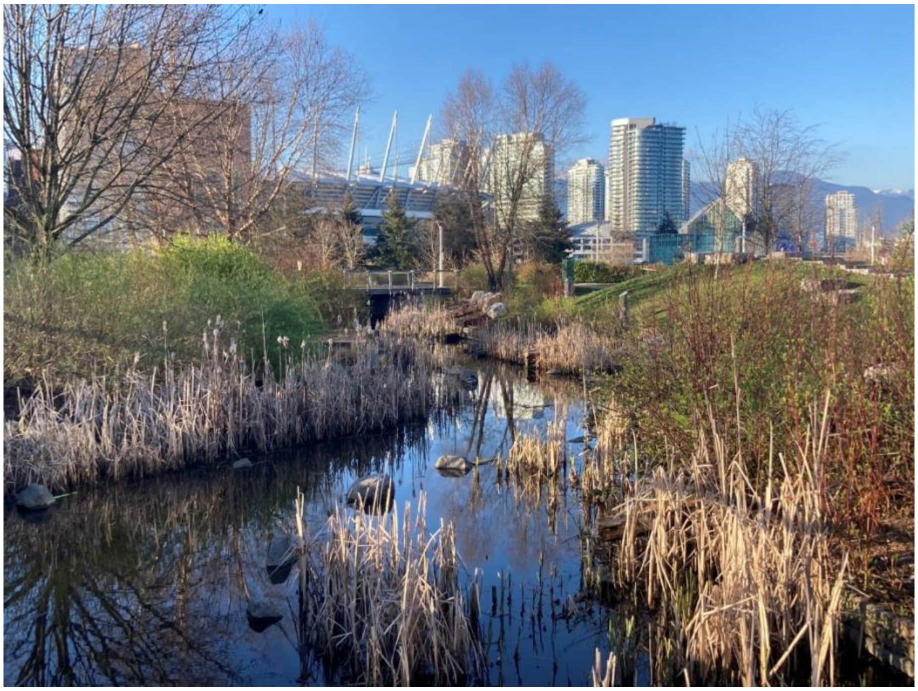
HIGHLIGHTS	DETAILS
Almost all B.C. coastal communities have undertaken some coastal flood adaptation actions, and there is a wide range in how active communities have been.	On average, B.C. coastal communities have undertaken 14 actions that address coastal floods. Of the 57 communities, 4 have not taken any coastal flood adaptation actions, while 7 have taken over 30 actions each. The number of actions taken, portfolio diversity, and the proportion of actions at a groundwork stage do not appear to be correlated with community population size or average household income.
Communities rely on different mechanisms to address flood risks.	Roughly 75% of communities have implemented actions related to land-use regulations, while 49% have implemented projects aimed at mitigating coastal flood damage. There has also been focus on capacity building and emergency preparedness actions, undertaken by 56% and 44% of communities, respectively. Most communities have action portfolios relying on multiple mechanisms. Only 5 communities took actions in only 1 action category. One common type of land-use regulation consists of development permit areas (DPAs). Damage mitigation actions included structural and non-structural measures.
Actions addressing flood risks reflect different long-term strategies.	Most communities (68%) are implementing some actions to accommodate flood events, while 54% of communities have “protect” actions that prevent hazards or their impacts through structural mechanisms. Only 4% of communities have implemented actions seeking to retreat from the coast.

	Most communities have taken actions seeking multiple strategies. Over 56% of communities are pursuing 2 or more long-term strategies, with an overall average of 1.5 strategies.
On average, 55% of the actions in each community have involved tangible changes in policies, institutions, or the built environment. The remaining 45% correspond to groundwork actions that inform or prepare for future actions.	Examples of tangible implemented actions include construction specifications, structural interventions, and land-use regulations, among others. Groundwork actions include technical studies, forming committees, or budget allocation. Only 2 communities have only taken groundwork actions, while 7 communities have only implemented actions involving tangible changes.

Recommended future research to improve risk understanding

1. **Expand data collection:** Increasing resources for data collection could allow for more sources of information to be consulted, expansion to other hazards, the database to be kept up to date, and additional information to be added.
2. **Conduct surveys with community officials:** Targeted surveys and interviews would provide insights as to factors that facilitate implementation of tangible changes as well as barriers preventing further action.
3. **Engage with First Nations communities:** Appropriate data collection should be conducted with First Nations communities to understand the actions they are undertaking or wish to undertake in relation to coastal floods. Incorporating Indigenous Knowledge would provide information on actions and approaches historically overlooked in Western land-use planning and risk management.
4. **Track B.C. coastal adaptation over time:** Monitoring actions against a baseline can help establish how communities are addressing coastal flood risk and becoming more resilient. It can also help identify disparities between communities and their need for support.

Engineered wetland in Vancouver (Mauricio Carvallo Aceves, 2024).



Resources

Resilient Coasts Canada platform: resilient-c.ubc.ca.

S.E. Chang, J.Z.K. Yip, T. Conger, G. Oulahen, E. Gray, and M. Marteleira, “Explaining communities’ adaptation strategies for coastal flood risk: Vulnerability and institutional factors,” Journal of Flood Risk Management, e12646, 2020. https://doi.org/10.1111/jfr3.12646

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Case Study 8: Assessing disaster risk and community capacity among 2SLGBTQIA+ coastal communities in B.C.

Natasha Fox, University of British Columbia

Introduction

British Columbia's Lower Mainland faces the growing threat of a major earthquake and tsunami along the Cascadia Subduction Zone (CSZ), a seismic hotspot capable of producing the world's largest earthquakes and catastrophic tsunamis.[37] Existing research on the interaction of social differences and uneven vulnerability and resilience to disasters highlights the added impacts on 2SLGBTQIA+ (Two-Spirit, Lesbian, Gay, Bisexual, Transgender, Queer or Questioning, Intersex, Asexual and gender diverse) people during and after disasters.[38] This project adds depth to understandings of 2SLGBTQIA+ community risk and resilience in B.C. by assessing local emergency management agendas relative to community needs and experiences.

Methodology

A series of semi-structured interviews with local 2SLGBTQIA+ community members, emergency coordinators, and community liaisons in emergency management offices in three coastal B.C. locations is the primary source of data. The data are supplemented with analysis of publicly available local earthquake and tsunami preparation and outreach materials on the websites of each of the three offices of focus. Data analysis is also supplemented by a case study in Lincoln County, Oregon, the location of a new 2SLGBTQIA+ community risk and disaster vulnerability initiative (facilitated by the investigator's capacity as a postdoctoral researcher, Oregon State University).

Findings / Learnings

HIGHLIGHTS	**DETAILS**
Emergency management offices understand the importance of community outreach in planning for a major disaster, but they do not have specific knowledge of or adequate plans in place to	In interviews with personnel in emergency planning offices in the three BC locations, interviewees expressed confidence that existing plans adequately addressed and incorporated 2SLGBTQIA+ community needs, yet they were unable to articulate what those specific community needs would likely be and had never intentionally engaged with these communities in outreach activities.

address 2SLGBTQIA+ community needs in a CSZ event.	Intentional engagement of these communities is a recommended improvement.
2SLGBTQIA+ communities in each of the three B.C. locations described a lack of adequate structures to integrate community concerns into local emergency planning and outreach agendas.	Each of the community members interviewed described concerns that local emergency management offices were unaware of the compounding risks impacting 2SLGBTQIA+ communities that may exacerbate their vulnerability to a CSZ earthquake and tsunami. For example, three interviewees noted lack of access to appropriate healthcare and community support as a concern in everyday life that would be exacerbated in a CSZ event. Recent windstorms and wildfires that caused road closures between Port Alberni and Nanaimo further cut off 2SLGBTQIA+ community access to inclusive healthcare during the period of road closure, for example. Two interviewees noted 2SLGBTQIA+ overrepresentation in unhoused and transient communities as a major concern for emergency notifications and evacuation to reception centres.
Emergency coordinators' awareness of and interest in the unique needs and concerns of 2SLGBTQIA+ communities prior to, during, and after a catastrophic CSZ earthquake and tsunami varied widely between locations of focus.	Two emergency management offices in B.C. described their community outreach and engagement efforts as designed to meet the needs of the whole community, yet they conceded that 2SLGBTQIA+ needs had not been considered. Another felt that having a small general population meant that a targeted approach was not needed due to a lack of local diversity. Another emergency coordinator asked to be introduced to research partners in local 2SLGBTQIA+ communities in order to develop those connections for future outreach.

Recommended future research to improve risk understanding

1. Future studies would benefit from scaling up the findings from this study, in geographical scope and types of hazards, and by including other historically marginalized and underserved communities of interest.
2. **Gather experiential knowledge:** Many local emergency managers and coordinators in this study stated that they were unaware of risk factors impacting 2SLGBTQIA+ communities. Engaging with 2SLGBTQIA+ communities directly (for example, through

listening sessions, focus groups, online information forums, and other methods) to understand lived experiences and knowledge around everyday vulnerability will enhance understanding of hazard vulnerability and resilience strategies specific to this group.

3. **Build relationships with community-based organizations:** Fortifying relationships with community-based organizations serving 2SLGBTQIA+ communities in locations vulnerable to CSZ hazards will help local emergency managers and coordinators identify and understand the needs and resilience strategies of this group.
4. **Share information:** Make data and information available to marginalized and underserved 2SLGBTQIA+ communities in locations, times, and ways that are meaningful and relevant to the community itself. Consider extending direct invitations to local community-based organizations to attend open house events on emergency preparedness, for example.

Resources

Natasha Fox, Jenna H. Tilt, Peter Ruggiero, Katie Stanton, and John Bolte, "Toward Equitable Coastal Community Resilience: Incorporating Principles of Equity and Justice in Coastal Hazard Adaptation," Cambridge Prisms: Coastal Futures 1 (2023): e36. https://doi.org/10.1017/cft.2023.24

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Disaster and Climate Risk and Resilience Assessment

(DCRRA)

Appendix D:

Equity, Diversity, and Inclusion

& Indigenous Knowledge Case Studies

Table of Contents

Introduction to equity, diversity, and inclusion & Indigenous Knowledge case studies

Understanding and addressing disaster and climate risk, including disproportionate impacts on certain groups as well as their unique strengths, can be well informed by different experiences and worldviews. These illustrative case studies can be found throughout the Provincial DCRRA and are collected here.

Case Study 1: When the river rises: A case study of Kwantlen First Nation's management of flood risk

Adapted from "When the River Rises: A Case Study of Kwantlen First Nation's Management of Flood Risk," with permission from the author, Carla Hanson and the Kwantlen First Nation.

Kwantlen First Nation (KFN) primarily resides on McMillan Island on the Fraser River, north of Langley in the Fraser Valley. The Nation has been historically restricted to this space, and several other undeveloped locations, through colonial policies tied to the Reserve section of the Indian Act.

McMillan Island is exposed to seasonal spring flooding each year during the freshet, putting KFN residents and infrastructure at risk. Despite this, KFN residents living on McMillan Island today would likely elect to stay on the island due to their deep connection to the land and water.

Colonialism impacts the KFN exposure and vulnerability to flooding and continues to influence emergency management practices today. Before the reserve system, the KFN would leave village sites on the banks of the Fraser River and move to higher grounds for the freshet season, returning to McMillan Island as a seasonal fishing camp. Colonial policies continue to exacerbate disproportionate vulnerabilities between KFN and non-Indigenous populations, where neighbouring off-reserve communities are far better protected through dikes and higher elevated lands.

In the recent past, there have been three major floods on McMillan Island—in 1948, 1972 and 2012. These floods impacted the island, where the east side is specifically prone to erosion. Over the last two decades, KFN has led projects to protect the island from erosion, including the installation of groynes and riprap. KFN has intimate knowledge of the island. Some of the most important aspects of flooding will always be site specific, which the Nation is physically, culturally and spiritually attuned to.

Alongside community-led initiatives and deep knowledge of the land, collaboration across communities and organizations is a strength of KFN's flood response and is core to their values. KFN holds collaborative, long-term relationships with some organizations, but work remains to improve other relationships. The community has identified that effective relationships exist when: 1. Community interests are prioritized; 2. There is space for reciprocal dialogue to learn from one another; and 3. Relationships are built on previous relationships that centre on trust, transparency and respect.

The word "Kwantlen" translates to "tireless runner" and speaks to the Nation's resilience in the face of all things, including flooding. The Nation has and continues to advocate for their safety, act in care of each other, and follow their seven traditional laws in their flood response: Generations, Generosity, Humbleness, Health, Happiness, Forgiveness and Understanding.

Capacity, culturally appropriate supports and access to up-to-date information remain a challenge for Kwantlen First Nation. Despite this, the Nation is working towards self-determination, which presents a challenge and many opportunities. In reclaiming the right to make decisions for their communities, one member stated, "That's why First Nations have to take it over—because it is a different culture. That's why it can't be led by somebody other than the First Nation, which again cycles back to colonialism and trying to fit First Nation culture into the mindset of the [various levels of government]."

Relationship and collaboration efforts present the best opportunities for overcoming challenges related to risk mitigation and response. By asserting self-determination and doing good work in in the space of risk management related to flooding, KFN has the opportunity to be prepared with the tools and relationships they need when the river rises. With continued effort in these spaces and by following their traditional laws, Kwantlen First Nation will continue to care for the safety of their community.

Case Study 2: Migrant labourers are especially vulnerable to heat

Adapted from "The Case for Adapting to Extreme Heat: Costs of the 2021 BC Heat Wave," with permission from the Canadian Climate Institute.

Migrant labourers in the agriculture sector are especially vulnerable to extreme heat events due to the strenuous nature of their work, the long hours and crowded accommodations. Within the Canadian agricultural sector, the majority of temporary migrant labourers are located in B.C., and in 2021, there were more than 10,000 migrant labourers in the province.

2021 was also the year of an unprecedented extreme heat event in B.C., where a late-June heatwave impacted communities across the province and beyond. A 2021 federal survey of temporary migrant labourers in the Canadian agricultural sector found that during the heatwave, 43 percent have no access to air conditioned or cooled accommodations. Some produce farms were forced to cancel shifts and tree fruit farms modified their harvesting time to after midnight to reduce heat stress on workers. Media reports from the Okanagan, an area greatly impacted by the heatwave, reported potentially unsafe living conditions among migrant farm workers due to a lack of cooling infrastructure.

Case Study 3: Pop-up camp for kids impacted by the 2021 White Rock Lake Fire

Adapted from "2021 United for BC Wildfire Recovery Fund Report" with permission from United Way BC.

In the summer of 2021, BGC Okanagan partnered with United Way to provide a pop-up recreation program for children of families evacuated by the White Rock Lake Fire. The evacuation impacted members of the Okanagan Indian Band and residents on the west side of the lake in Vernon.

Because of the fires, many children had been stuck in hotel rooms for days on end—unable to play outside, due to poor air quality, or to access to indoor opportunities, due to unaffordability. Parents were faced with a high-stress situation, trying to call insurance companies and access resources, while keeping their children happy and occupied.

BGC's pop-up recreation program provided children with a safe and friendly environment to have fun, make friends and receive the help of supportive adults. The program was held at the BGC gym, adjacent to the Emergency Support Services (ESS) reception, so evacuees could drop their children off while receiving ESS support. The program was intentionally low-barrier—it didn't require any pre-registration or sign-up, provided breakfast and lunch, and was free to attend.

The program allowed children to play sports and games, make crafts, have glow stick parties, be taken on local walks, go rock wall climbing, watch movies and much more.

The staff at BGC witnessed many signs of the trauma and stress that children had experienced. A child referred by a local social worker had been struggling and couldn't leave his mom's side. Before long, the staff at BGC helped the child make friends with other children, allowing his mom to go and access ESS supports. Another family was new to the area and had been evacuated from their home after two weeks. The program helped turn a stressful and chaotic introduction into a new community into a safe, supportive and fun experience.

Case Study 4: Community resilience to seismic events: A case study of Haida Gwaii

Adapted from "Community resilience to seismic events: a case study of Haida Gwaii (Thesis)," by Deborah Pearson.

Small, remote communities situated along the Pacific Northwest coast of British Columbia are vulnerable to seismic events, including earthquakes and near- and far-field tsunamis. Haida Gwaii is a seismically active archipelago of ~150 islands, with a population of ~4,500 people spread across six small communities. On October 27, 2012, a 7.8 M earthquake occurred. The epicentre was approximately 80 km seaward off the west coast of Haida Gwaii. This was the second largest earthquake recorded in Canadian history, and tremors were strong enough to be felt up to 1,500 km away.

Although this was a large seismic event, injuries to people and damage to infrastructure were minimal, likely in part because the epicenter was remote from communities and the resultant tsunami occurred when boaters and tourists were not typically present. The seismic disturbance did however result in psychosocial impacts to community members, and provide an opportunity to reconsider hazard preparedness on Haida Gwaii.

Despite legislative requirements to be prepared for hazard events, there has been a long-standing concern regarding earthquake preparedness in B.C. It is especially important for rural and remote communities to plan and prepare for hazard events, because their unique characteristics render them particularly vulnerable to disaster impacts and outcomes.

Due to the remote location, development in low-lying areas and socioeconomic challenges, Haida Gwaii communities are highly vulnerable to seismic events. However, prior to the 2012 earthquake, community and emergency planning for seismic events was not a priority and as such, citizens, stakeholders and local authorities were not well prepared for a significant seismic event. Low levels of awareness, limited capacity and resources inherent to small remote communities, and lack of policy direction from senior levels of government led to planning that was limited in scope and quality. Policies were found to be heavily focused on response activities, and few strategies were implemented to reduce vulnerability as well as and short- and long-term risks. As well, response planning was not robust and plans were not fully exercised, evaluated or maintained. The lack of preparedness in place for the 2012 earthquake, inadvertently contributed to the vulnerability of these small, remote, coastal communities.

The resilience of Haida Gwaii citizens, stakeholders and local authorities was tested by the 2012 earthquake. The event provided the impetus for local authorities and emergency managers to obtain capacity and resources, and improve education programs, community warning systems, and evacuation and response plans. As well, citizens have gained knowledge and have become engaged as active participants in emergency planning, which helps to build capacity and resilience in the community. It is expected that the new community-based Emergency Response Plans that align with local knowledge, skills, capacity and resources will help to improve response efficiency and build capacity.

The communities of Haida Gwaii are deeply connected to the land and waters, and living "on the edge" has taught the people and communities how to make do with less, navigate challenges and change, and work together to sustain their way of life and their communities. The strong social capital resources on Haida Gwaii were embodied in the statement "our people are our strongest thing," which perhaps shows the true extent of Haida Gwaii's resiliency and adaptive capacity.

Case Study 5: Gitxsan Rez-ilience

Adapted from "Gitxsan Rez-ilience" (Canadian Climate Institute, 2022), with permission from the author, Janna Wale.

For millennia, Indigenous Peoples have maintained connections to their seasonal round activities. For Indigenous communities, these seasonal, land-based practices can inform values, protocols and understandings of climate resilience, and to a holistic and grounded demonstration of rez-ilience: their own understanding of how to be resilient, and a reference to the term "resilience" and the system of reservations created under Canada's federal Indian Act. For example, The Gitxsan People live at the unceded confluence of the Skeena and Bulkley Rivers, where the land informs Gitsenimx, the language spoken by Gitxsan People. Naadahahlhakwhlinhl (interconnections with all living things), for example, emphasizes the holistic relationship the Gitxsan People hold with their lax yip (territory).

Despite colonial history and ongoing impact of the Indian Act and Residential Schools, Gitxsan People continue to enact their hereditary governance and live in tune with the annual cycles of changing seasons. However, the seasons are less predictable today than they were in past times due to the changing climate.

Research with Gitxsan community members illuminates how seasonal rounds are changing, and how these changes are altering Gitxsan ways of life. For example, reduced berry production due to heat stress is contributing to changes in moose migratory patterns within the territory—a cascading effect that both destabilizes the ecosystem and impacts Gitxsan food security. Similarly, the ecosystems that support salmon, a cultural keystone for the Gitxsan People, are also being degraded.

As the seasonal rounds shift, so too will the culture, language and identity of the Gitxsan People. However, the change in the relationship to land does not equate a loss in relationship. Rez-ilience supports redefining Gitxsan relationships with the land. In this way, Gitxsan people are actively demonstrating climate rez-ilience (using past applications of resilience shown by their ancestors to inform self-determined futures). Rez-ilience is strength-based, holistic and will adapt, grow and change, as will the Gitxsan People. Gitxsan rez-ilience is about upholding traditional laws, ceremonies, protocol and responsibilities, weaving together lessons from the past to face today's challenges. Gitxsan rez-ilience is relational and kin-centric. It honours the relationship of the Gitxsan to and knowledge of their lands and waters, and their continued assertion of sovereignty, stewardship and presence on their territories. Understanding rez-ilience and honouring First Nations responsibilities and relationships to the land is critical to restoring the balance of our social and ecological worlds.

First Nations Knowledge and understanding of climate rez-ilience—a kin-centric and relation-based approach—needs to be reflected in government climate policies and management strategies. There is a need for responsibility, accountability and relationships to inform place-based approaches to climate policy.

The Gitxsan term "Yukw na hagwil yin," translates roughly to "learning to walk softly"—taking care of how you live on the land and how you act—and is a reminder of the responsibility toward generations to come. As each Nation holds its own history, laws and governance systems, each Nation too has a different expression of rez-ilience. Building rez-ilience is a journey that began with ancestors and will continue with the next generation of First Nations People, who are meant to be leading this work.

Figure 1: Harvesting fireweed blossoms that will later be turned into fireweed jelly (photograph by Janna Wale).

Figure 2: Processing sockeye salmon to preserve for the winter months (photograph by Janna Wale).

Case Study 6: Losing a sense of home: Merritt flooding in 2021

Adapted from "What I Saved from the Disaster" (2023), with permission from the author, Francesca Fionda, and interviewee Rochelle Rupert.

While Rochelle Rupert used to appreciate the presence of the Coldwater River behind her property in rural Merritt, B.C., things changed in November 2021 when the river breached its banks and flowed into her home. The flooding was part of an atmospheric river event, which brought unprecedented amounts of rain across the province, causing immense devastation to many communities, including Merritt. The flooding came after an intense fire season, with three fires in proximity to Merritt—Logan Lake Fire, Lytton Fire and Coldwater Fire. That year, Rochelle thought the fires were the main evacuation threat to her community—but in fact, it was flooding caused by the atmospheric river event and undoubtedly exacerbated by the fires.

The flood event devastated Rochelle's home. After the flood, Rochelle's entire place was covered with mud and debris. The flooding also uncovered a hidden oil tank under the crawl space of her living room floor that leaked due to the pressure of the water and damaged the flooring throughout her home. For eight to nine months, while some of her neighbours returned to their homes, Rochelle didn't know if her home was salvageable. In spring of 2023, Rochelle was still working to repair her home. The foundation of her garage had shifted, the roof had become unsteady, and flooring within the house had to be removed.

Rochelle reflects on the aftermath of the damage, recalling: "You wouldn't believe the muddy zombies we were for weeks," as she cleaned up and removed debris that the river brought to her home on its course through the city.

After the flooding event, the evacuation process and timelines were unclear. The damages to her house were so great, and the recovery process so lengthy, that more than a year after the flood she still was not able to move in, let alone move on. In 2023, Rochelle was caught between repairing her home or selling it.

And for Rochelle, there is a difference. “I don’t really care about material possessions. The thing that depressed me the most about the flood was not the loss of the things I owned, but the loss of the feeling of having a home.”

For Rochelle, “It was that place where you’re comfortable, that place that’s yours, that place you can go and relax, that place you can shield yourself from others, that place you can recoup, that place where you re-energize. That place for me was gone and didn’t exist anymore.”

In the early summer of 2024, Rochelle is back in her home, which she recently sold. She is moving into a camper van. After the devastation and prolonged restoration process, she no longer wants to own a home. The experience has altered her lifestyle and understanding of home.

Figure 3: Rochelle Rupert walks along the floorboards of her house, devasted by the Merritt flooding in 2021. Photo by Jen Osborne, with permission.

Case Study 7: Disproportional impact of climate and disaster events on women with intersecting identities

Adapted from "Climate Change, Intersectionality and GBA+ in British Columbia" and "Social Impacts of the 2018 Grand Forks Flood," with permission from Dawn Hoogeveen

Women, particularly women with intersecting identities, are disproportionately impacted by climate change and disaster events. Women's vulnerabilities often stem from socio-economic status and greater caretaking and domestic responsibilities.

Due to discrimination and family responsibilities, women often work lower paid jobs; flexible jobs; and, in many cases jobs, with lower benefits than their male counterparts. This impacts women during climate change events, as lower socio-economic status results in vulnerability due to decreased adaptive capacity. Further, women of colour and newcomer women are even more likely to work lower paid jobs.

This reality becomes apparent during heatwaves or when communities are impacted by wildfire smoke from a nearby fire. Homecare workers (who are primarily women and often women of colour or newcomer women) are required to provide more care and more frequent checks on their patients. Simultaneously, women often need to juggle their own family and domestic responsibilities in addition to their paid work. These responsibilities often increase during climate events and disasters, as other support systems like school and daycares close down. The result is that homecare workers are exposing themselves to potentially harmful environments (working and travelling during heat and smoke events) and are working more than usual, while also having to tend to increased family and domestic care duties.

Increased caretaking roles for women has also been documented during floods, including the 2018 Grand Forks Flood. On May 10, 2018, following a week of high temperatures and three days of heavy rainfall, Grand Forks and the Boundary region experienced a major flooding event. This was the worst flooding event recorded in the area, where the confluence of the Kettle and Granby Rivers exceeded a 200-year flood level. The flood had a myriad of impacts on the community, and significantly impacted certain populations including women. An interview participant stated: "Women became the focal point of maintaining cohesive family units and extended care. It became them managing their own family and children and others." Further, interviews brought light to the fact that the burden is particularly heavy for women who were living in poverty before the flood, single mothers and elderly women.

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Case Study 8: Being emergency-ready: The Skeetchestn Indian Band

Adapted from "Addressing the New Normal: 21st Century Disaster Management in British Columbia, Being Emergency Ready: The Skeetchestn Indian Band," with permission from Chief Maureen Chapman and Don Ignace.

The Skeetchestn Indian Band, located west of Kamloops Lake, developed their all-hazards plan in the mid 2000s. The plan covers a wide range of situations—fires, floods, earthquakes and pandemics. The plan also extends to include transportation and pipeline-related incidents, as the Band's territory includes portions of the Trans-Canada Highways, two railways and a natural gas pipeline.

Don Ignace, the Incident Commander with the Band's Emergency Operations Centre, reflects that given the rapid onset of hazards, including the 2017 wildfires, being prepared is not just about having a plan, but ensuring that it is up to date too.

"Having the right people in place and making sure you have the right person attached to the plan, who knows it intimately, is key," he says. "Some people [in other communities] had an emergency plan, but they didn't know about it. Some people didn't even have time to open the document, the fire went through the community [that fast]. [Being prepared is about] having people who know about the plan, so they can activate it when it is time."

Having a plan and being prepared to activate it is especially critical for First Nations communities. Don adds, "We're not a municipality; we are our own governments, so First Nations communities should definitely have their own plans, as they are on their own until they can get resources through Indigenous Services Canada (ISC)—so they must be able to look after themselves for a period of time."

Beyond emergency plans and tactics, Don believes that local/Indigenous Knowledge of the land is invaluable in thinking about planning for wildfires and other emergencies.

"Who knows more than the people that actually lived on the ground and walked it—walked every little rocky outcrop and crevice. Ever since they were kids, they were out there hiking, picking berries, and hunting with their parents and grandparents, learning about these resources." He adds, "They were very resourceful when it came to helping the RCMP navigate the area, as well as [helping] members of the B.C. Wildfire Service team [identify] where they should be putting some fireguards, identifying the surrounding terrain and access points. Local knowledge was key, not only in-house here in our emergency operations centre, but also on the ground."

Case Study 9: Pop-up cooling tents in Kelowna to protect the unhoused and insecurely housed during extreme heat

Adapted from "Heat Response Planning for Southern Interior B.C. Communities: A Toolkit," with permission from the author Kerri Klein.

During the 2021 heat dome event in Kelowna, when daytime high temperatures reached 45.7°C, members of the Lived Experience Circle on Homelessness quickly recognized that community cooling centres were inaccessible and did not meet the needs of people experiencing being unsheltered.

In response to this, a collection of over 50 community partners were mobilized. Partners included Interior Health, the City of Kelowna, BC Housing, RCMP, Canadian Mental Health Association and the Ki-Low-Na Friendship Society, all guided by the Central Okanagan Journey Home Society, to create a more accessible option for the unhoused and insecurely housed populations in Kelowna during this unprecedented extreme heat event.

"Pop-up cooling tents" were developed and implemented in accessible locations downtown. Peer Navigators led operations within the pop-up cooling tents, which supported accessible first points of contact. Peer-run Personal Belonging Storage Programs operated in parallel within the downtown core, providing secure locations for people to leave their belongings while accessing the pop-up cooling tents during the day.

The quick, adaptive pop-up cooling tent program was possible because of strong governance structures, communication pathways and coordination between multiple organizations, outreach teams and people with lived experiences. Community outreach was an enabling factor that facilitated an understanding of community needs and supported the development of a safe and accessible response to the heat dome for the unhoused and insecurely housed in Kelowna.