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

March 24, 2025 Project 1362002

Sage On Earth Consulting
2317 Kirkstone Road
North Vancouver, BC, V7J 3L9 Canada

Attention: Sahar Safaie, M.Eng., Director

DCRRA Hazard Exposure Analysis

Please find the report attached documenting work undertaken by BGC Engineering Inc. (BGC) to deliver a geospatial hazard exposure analysis for the Disaster and Climate Risk and Resilience Assessment (DCRRA). We appreciate the opportunity to collaborate with you on this challenging and interesting project.

Should you have any questions, please do not hesitate to contact the undersigned.

Yours sincerely,

BGC Engineering Inc.
per:

Kris Holm, M.Sc., P.Geo.
Principal Geoscientist

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
May 24, 2024	0	Draft Issue
July 4, 2024		Final Issue
October 1, 2024	1	Final (Rev 1) Issue
March 24, 2025	2	Final (Rev 2) Issue

CREDITS AND ACKNOWLEDGEMENTS

BGC would like to acknowledge the following individuals for their contributions to this project.

- Matthew Buchannan
- Matthew Teelucksingh
- Jane Wang
- Richard Carter
- Sophia Zubrycky
- Melissa Hairabedian
- Martin Zaleski
- Marc-André Brideau
- Elisa Scordo
- Katherine Johnston
- Patrick Grover
- Aron Zahradka
- Kris Holm
- Caio Stringari
- Alex Mitchell
- Mark Halverson.

BGC would also like to express its appreciation for the support and input provided by external reviewers/contributors including:

- Ryan Reynolds (Resilience Mapping Canada Ltd.)
- Sahar Safaie (Sage on Earth Consulting Ltd.)
- Corey Froese (Wavelength Advisory Services Ltd.)
- Murray Journeay (Emeritus Scientist, Geological Survey of Canada).
- Jing Zhang, Julie Scott-Ashe, and Gurdeep Singh (GeoBC)
- Sage Team Hazard and Value Working Group co-chairs and members.

LIMITATIONS

BGC Engineering Inc. ("BGC") prepared this document[2] for Sage On Earth Consulting[3] and Government of BC. This document is only intended for the Client's use for the specific purpose or project identified herein. BGC is not liable for any loss, injury, or damages arising from any unapproved use or modification of this document.

Any use or reliance which a third party makes of this document is the responsibility of the third party and is at such third party's own risk. BGC accepts no responsibility for damages, if any, suffered by any third parties as a result of their use of this document.

This document contains BGC's professional opinions on the specific issues identified herein, based on the information available to BGC when BGC prepared this document. While preparing this document, BGC relied on information BGC received from the Client or other sources. Unless otherwise stated in this document, BGC did not independently verify such information, and BGC assumed that such information is accurate, complete, and reliable. BGC is not responsible for any deficiency, misstatement, or inaccuracy in this document due to errors or omissions in information provided by the Client or third parties.

This document may include or rely upon estimates, forecasts, or modeling analyses (e.g., results or outputs of numerical modeling) that are based on available data. Such estimates, forecasts, or modeling analyses do not provide definitive or certain results. The Client is solely responsible for deciding what action (if any) to take based on any estimates, forecasts, or modeling analyses.

BGC prepared this document in accordance with generally accepted practices for similar services in the applicable jurisdiction. BGC makes no warranty (either express or implied) related to this document. BGC is not responsible for any independent conclusions, interpretations, extrapolations, or decisions made by the Client or any third party based on this document. The record copy of this document in BGC's files takes precedence over any other copy or reproduction of this document.

BGC staff use their judgment in the preparation of geospatial data (Project Outputs) based on their knowledge of the geospatial software, and data inputs. Persons using the Project Outputs must familiarize themselves with those factors before using the Project Outputs. The interpretation of any results is the sole responsibility of the person making such interpretation. Any assistance BGC provides to any person in their use of the Project Outputs does not affect this responsibility.

[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).

BGC relied on third-party sources for estimates and modeling analyses. BGC did not verify or validate third-party data, which was used on an ‘as is’ and ‘as available’ basis. No warranty is made or implied by BGC that such third party data are correct, complete, reliable, current, or fit for any purpose. Use of such third party data may be subject to additional terms and conditions.

The Project Outputs do not represent guaranteed, complete, or error-free representations of actual ground conditions. The Project Outputs only represent BGC’s good faith estimations or analyses of certain issues or conditions, based on available data. BGC makes no representation, guarantee, or warranty that the Project Outputs are accurate, complete, or fit for any purpose.

BGC will not be responsible or liable for any loss, injury, damage`, or other liability arising in whole or in part from any of the following: (a) modification of any Project Outputs by anyone other than BGC’s staff; (b) use of any Project Outputs for any project or purpose other than the specific project and purpose for which BGC prepared the Project Outputs; (c) use of or reliance upon the Project Outputs after site conditions change; (d) failure of anyone other than BGC’s staff to properly use or interpret the Project Outputs; (e) Client’s independent conclusions, interpretations, extrapolations, or decisions based on the Project Outputs; or (f) any third party’s use of or reliance on the Project Outputs.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

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.

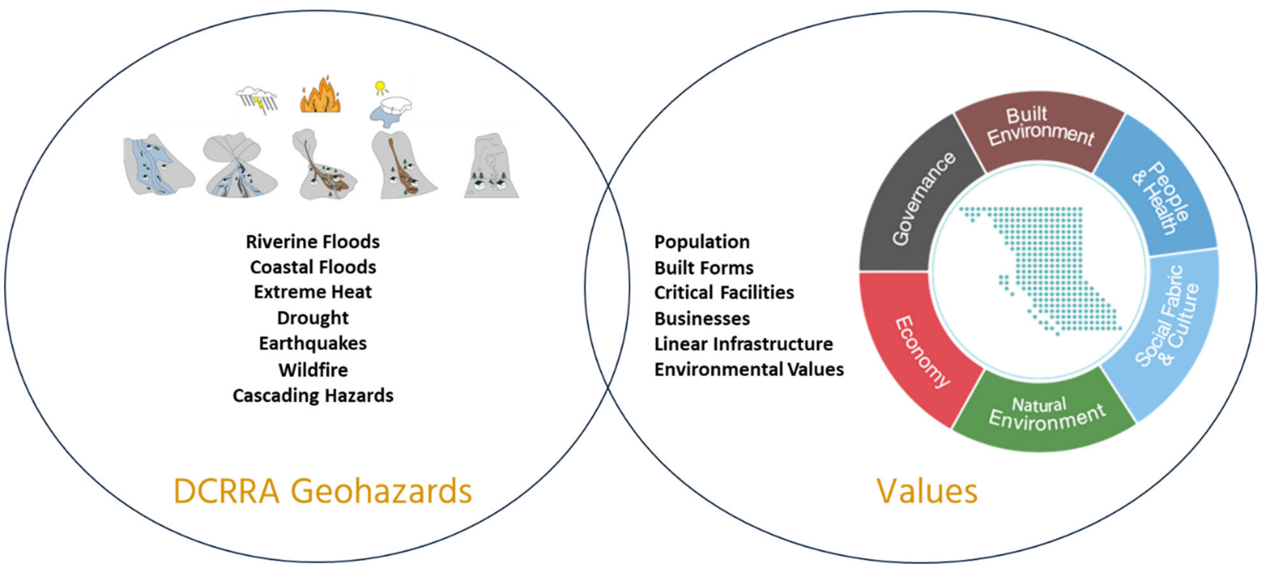


Figure 1-1 Conceptual illustration of the hazard exposure analysis objective: to identify the presence and characteristics of valued assets in areas potentially subject to the hazard types included in the DCRRA (as suggested by intersection of the two ovals).

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).

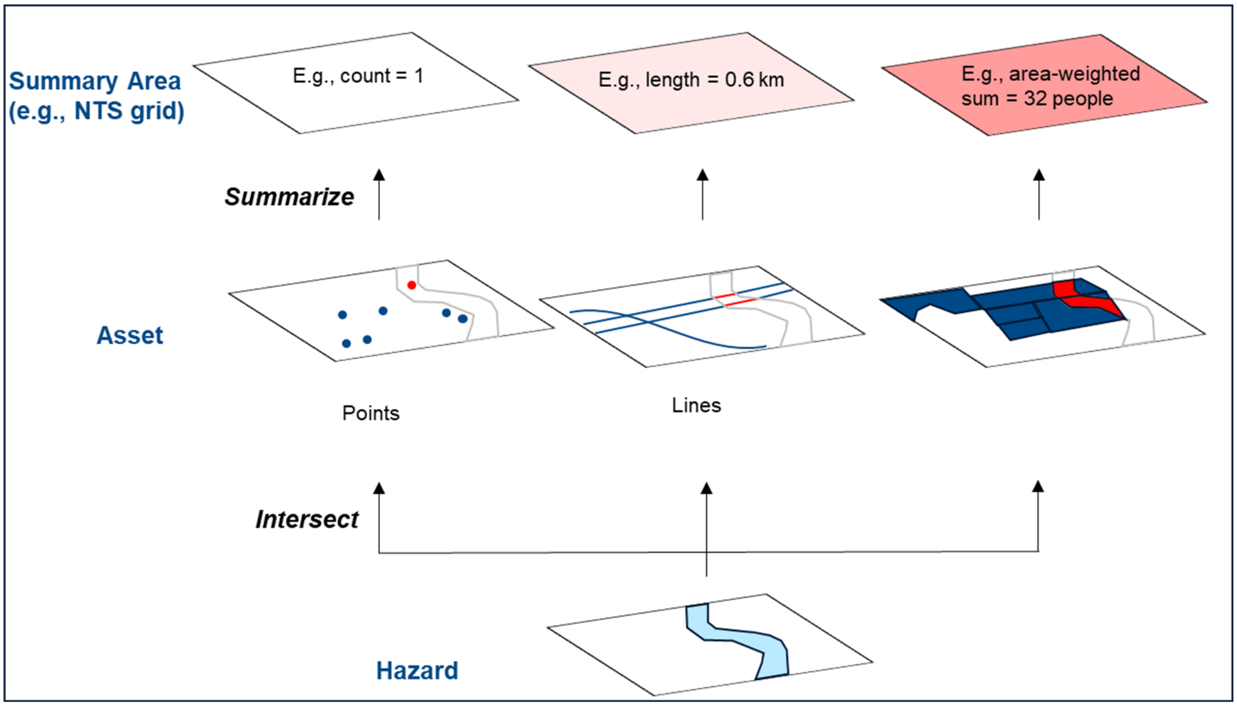


Figure 2-1 Conceptual diagram outlining the hazard exposure analysis workflow.

[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.

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

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 km^2 (example map of hazard extent).

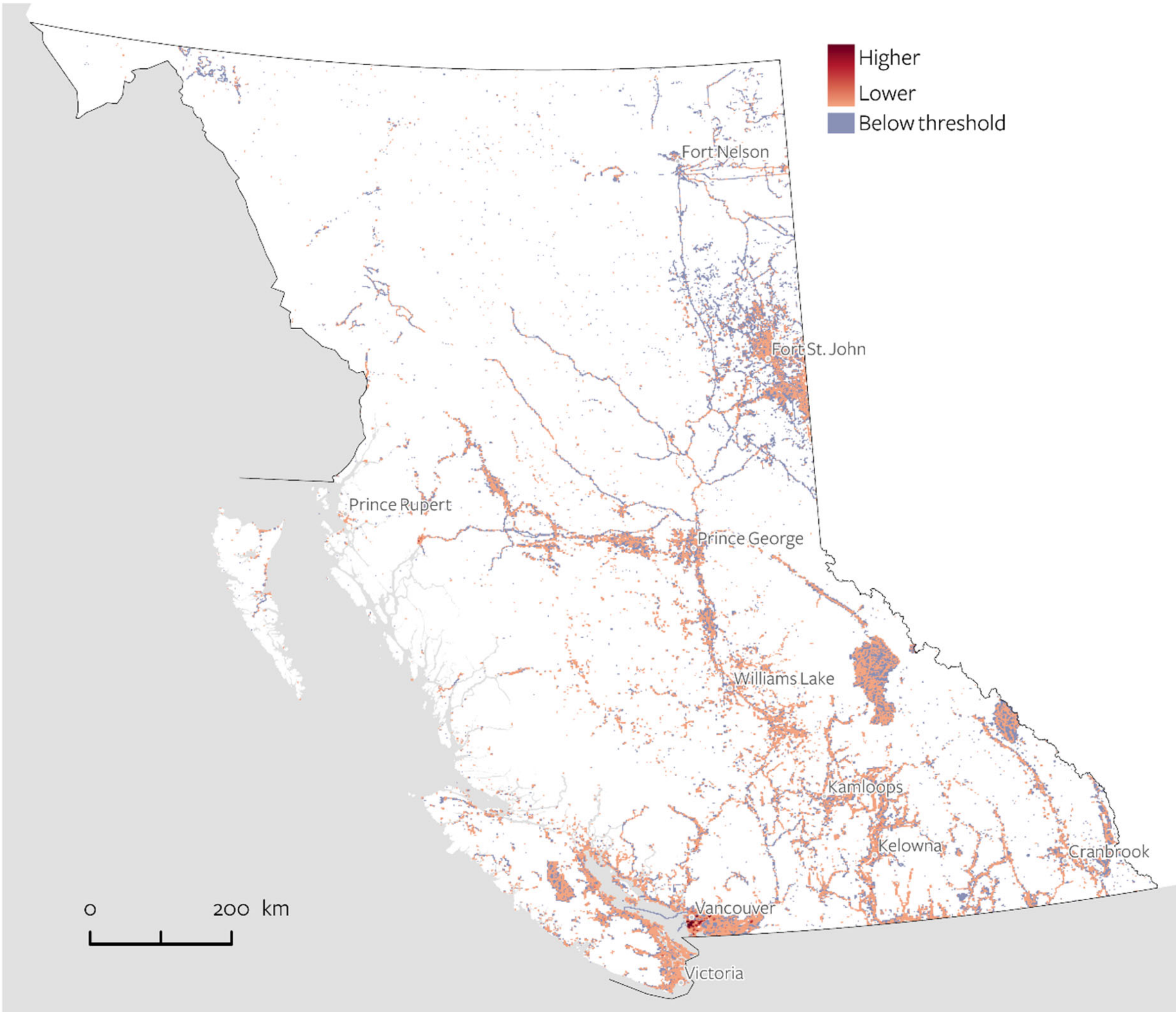


Figure 3-2 Built Form improvement values potentially exposed to riverine floods, based on the flood hazard extents shown in Figure 3-1 (example map of hazard exposure).

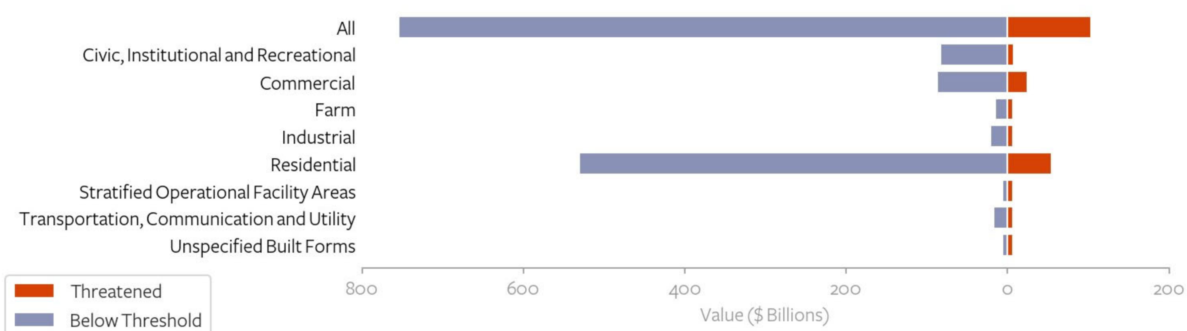


Figure 3-3 Types of Built Form improvements potentially exposed to riverine floods, based on the flood hazard extents shown in Figure 3-1 (example plot of hazard exposure).

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,

BGC Engineering Inc.
per:

PROFESSIONAL PROVINCE OF K. W. HOLM # 31207 BRITISH COLUMBIA GEOSCIENTIST

Mar 21, 2025

Kris Holm, M.Sc., P.Geo.
Principal Geoscientist

Richard Carter, M.Sc.
Earth Scientist

PROFESSIONAL PROVINCE OF M. HAIRABEDIAN # 44495 BRITISH COLUMBIA GEOSCIENTIST

March 21, 2025

Melissa Hairabedian, M.Sc., P. Geo.
Senior Hydrologist

PROFESSIONAL PROVINCE OF S. T. ZUBRYCKY # 56044 BRITISH COLUMBIA ENGINEER

MARCH 21, 2025

Sophia Zubrycky, M.A.Sc., P.Eng.
Geological Engineer

PROFESSIONAL PROVINCE OF Dr B C EATON # 31076 BRITISH COLUMBIA GEOSCIENTIST

March 21, 2025

Brett Eaton, Ph.D., P.Geo.
Principal Geoscientist

Reviewed by:

Elisa Scordo, M.Sc., P.Ag., P.Geo.
Senior Hydrologist

Marc-André Brideau, Ph.D., P.Geo.
Senior Engineering Geologist

EGBC Permit to Practice, BGC Engineering Inc. 1000944

KH/ES-MAB/kj/mm

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.

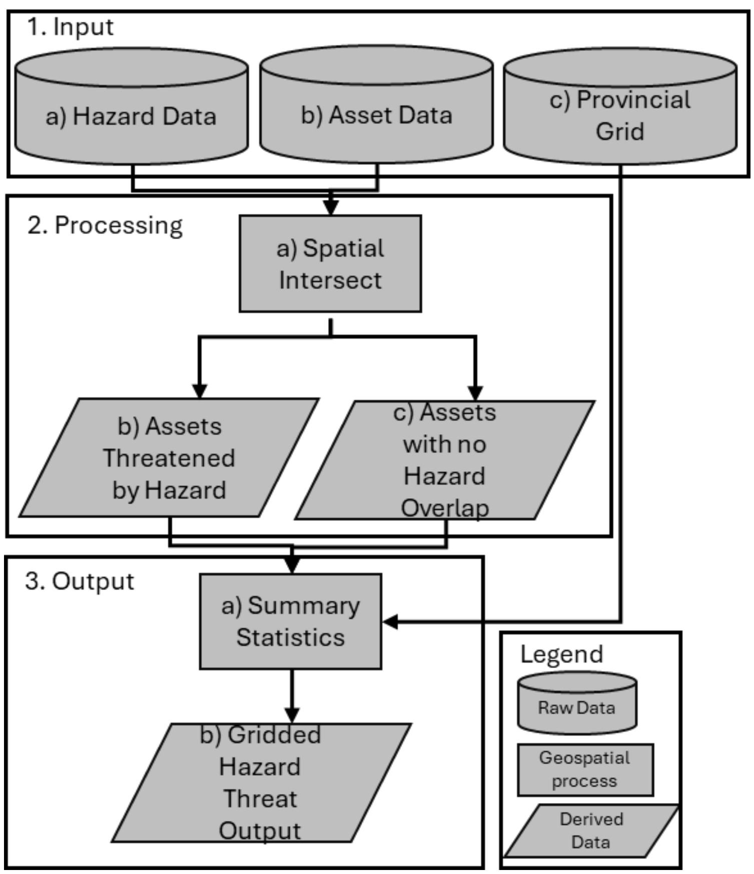


Figure A-2-1 Overview of hazard exposure analysis workflow.

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, 99th 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.

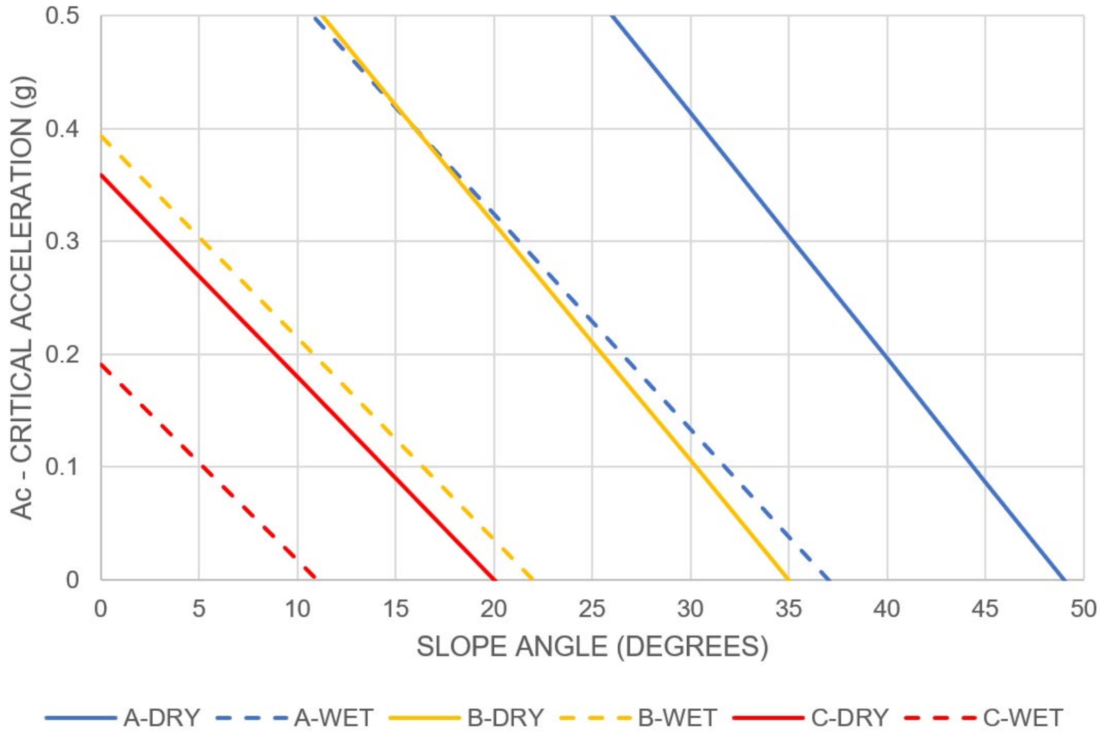


Figure A-4-1 Critical acceleration (Ac) related to geologic groups (A, B, C), slope angle, and saturation (dry, wet).

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].

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

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.

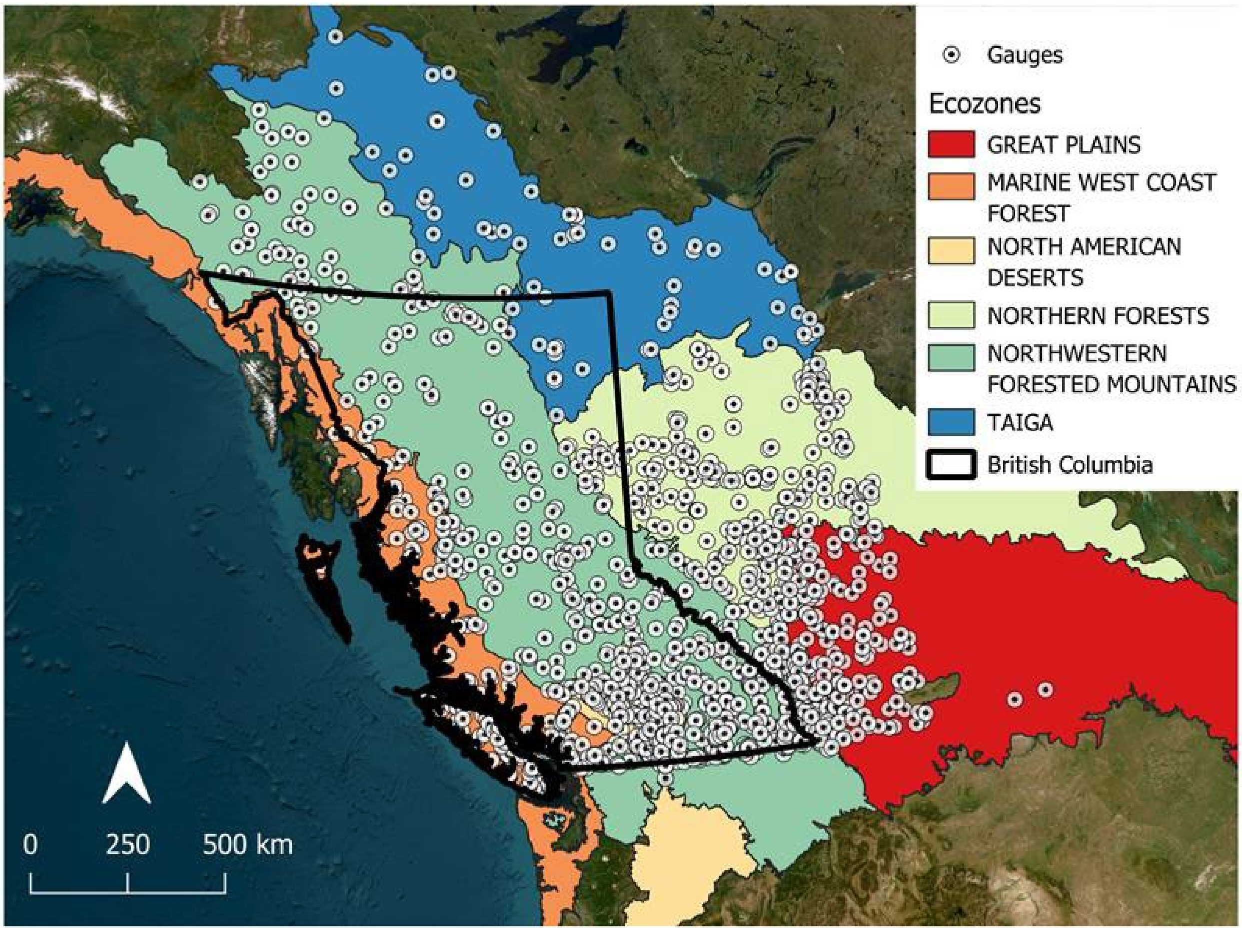


Figure A-5-1 Ecozones of BC.

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.

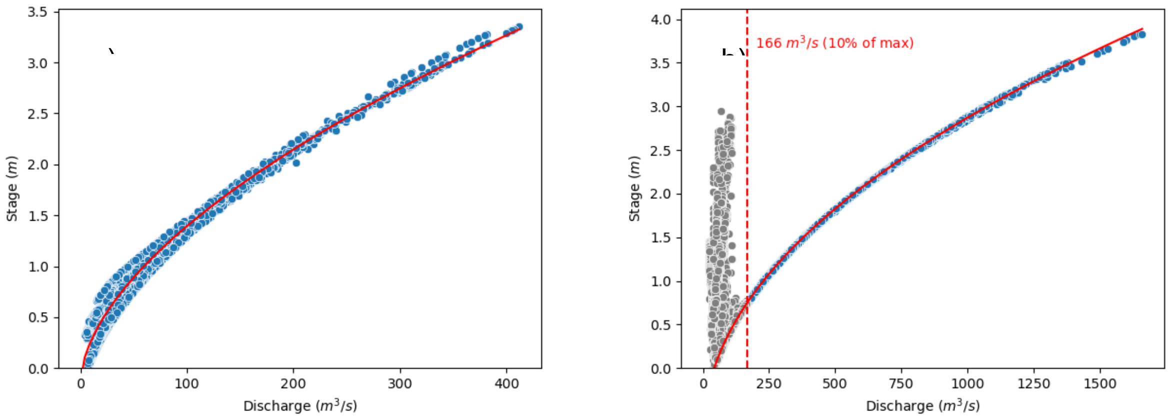


Figure A-5-2 Example rating curve for a) Pack River at the Outlet of McLeod Lake (07EE010) hydrometric station and b) Finlay River above Alie River (07EA005) hydrometric station. Both stations are in the Northwestern Forested Mountains ecoregion. Gray circles show data points removed from the analysis.

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.

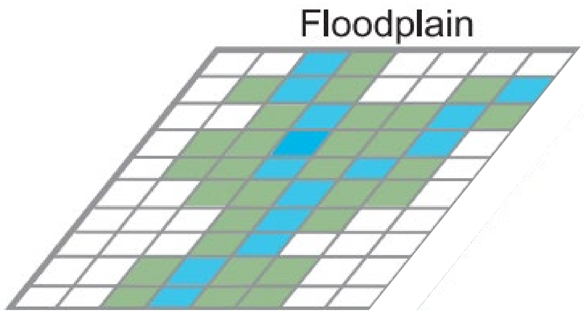


Figure A-5-3 Conceptual model of the gridded layer that is derived by defining grids as floodplain whose elevations are lower than the corresponding stream network flow levels. Blue depicts inundated cells while green shows non-inundated grid cells along a stream segment (Nardi et al., 2019).

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.

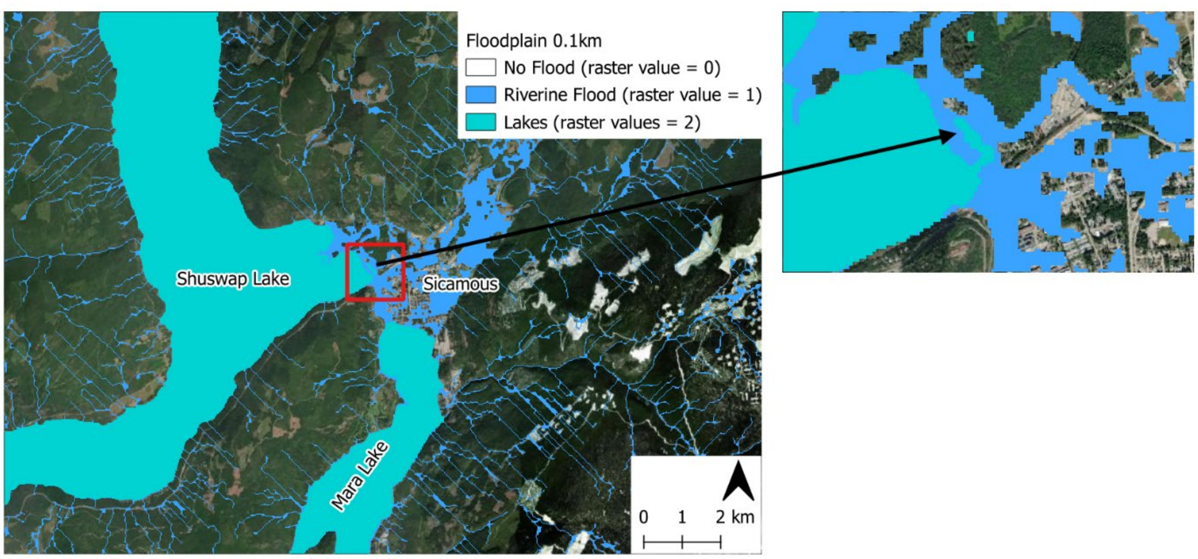


Figure A-5-4 Example of area where waterbodies were merged with the Tier 1 floodplain map.

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

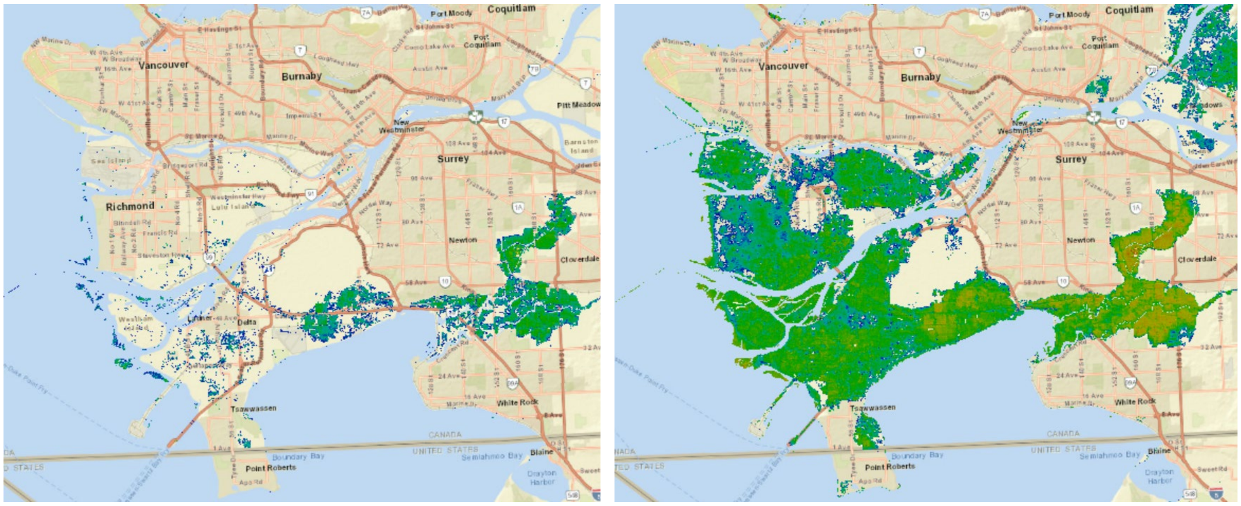
The hazard exposure analysis methodology was applied for coastal flooding as described in Section A-2 for all assets.

A-6.5 Gaps and Limitations

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

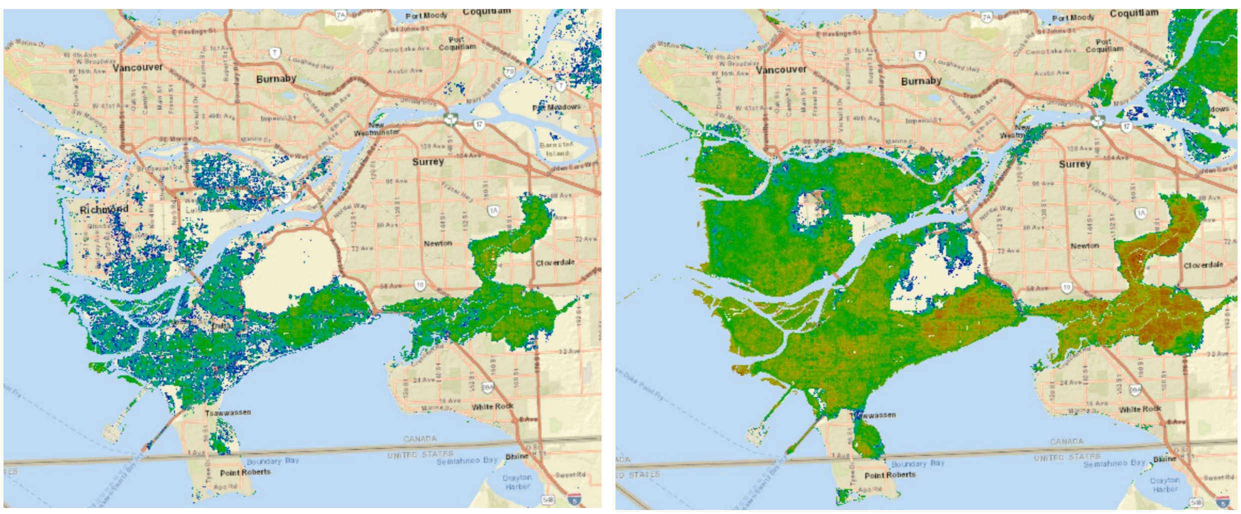
- Oceanic data used in the analysis was converted from MSL and interpolated between data points. The process of conversion and interpolation adds uncertainty in the flood layer.
- Oceanic data projections for storm surge and SLR were limited to the RCP8.5 scenario, which is representative of higher greenhouse 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.

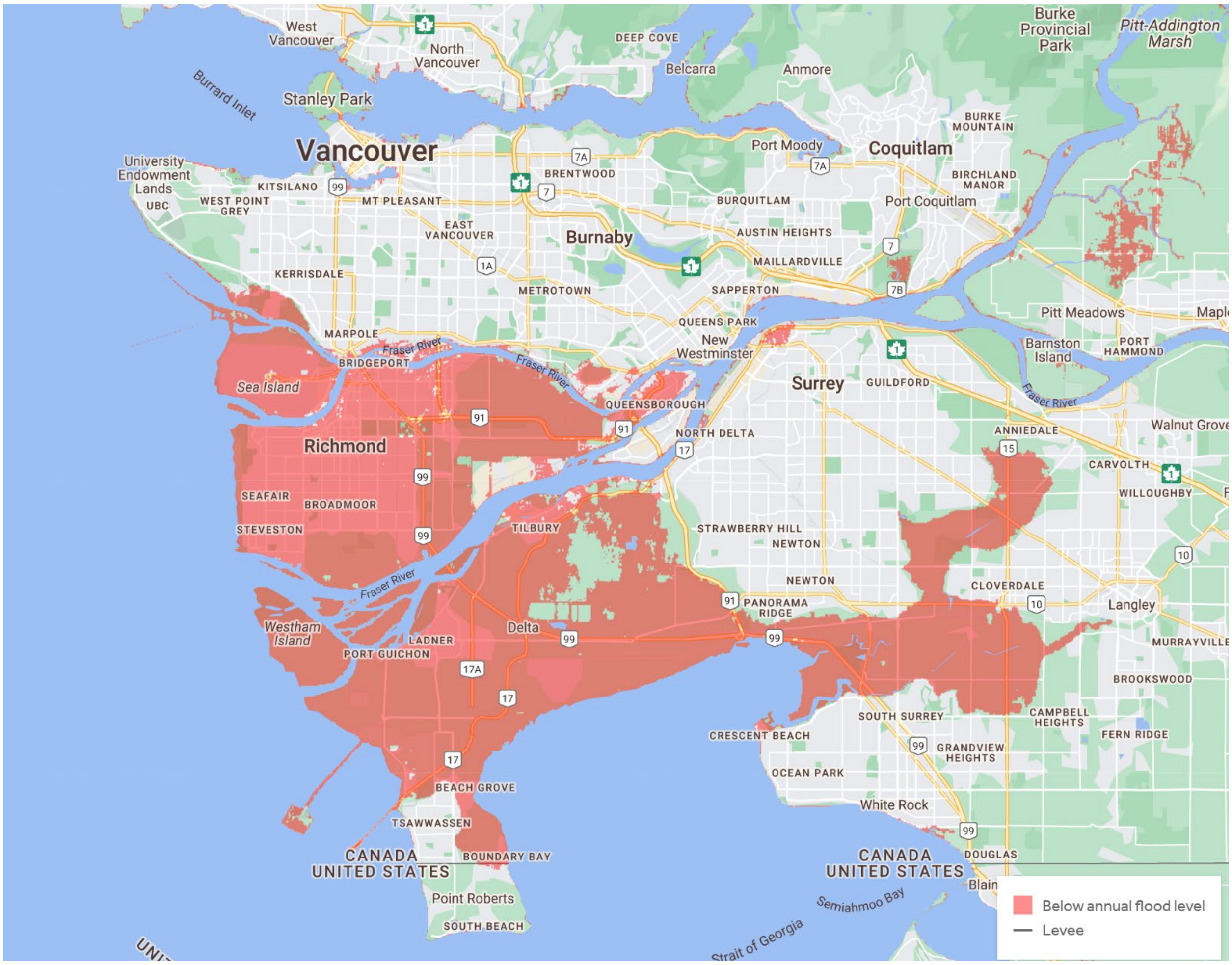


Figure A-6-3 Example of coastal flood inundation screening-level extents for the Lower Mainland for 2100 from Climate Central[6].

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).

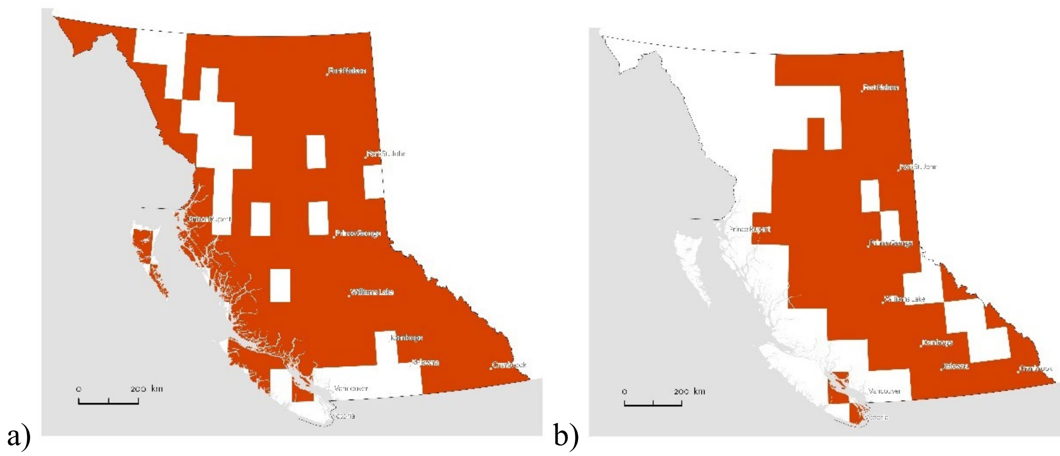


Figure A-8-1 Extreme (50-year) SPEI for the reference period (1950 to 2014) (a) and future period (2041-2070) (b). As noted above, the future image (right) shows areas projected to experience more drought.

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).

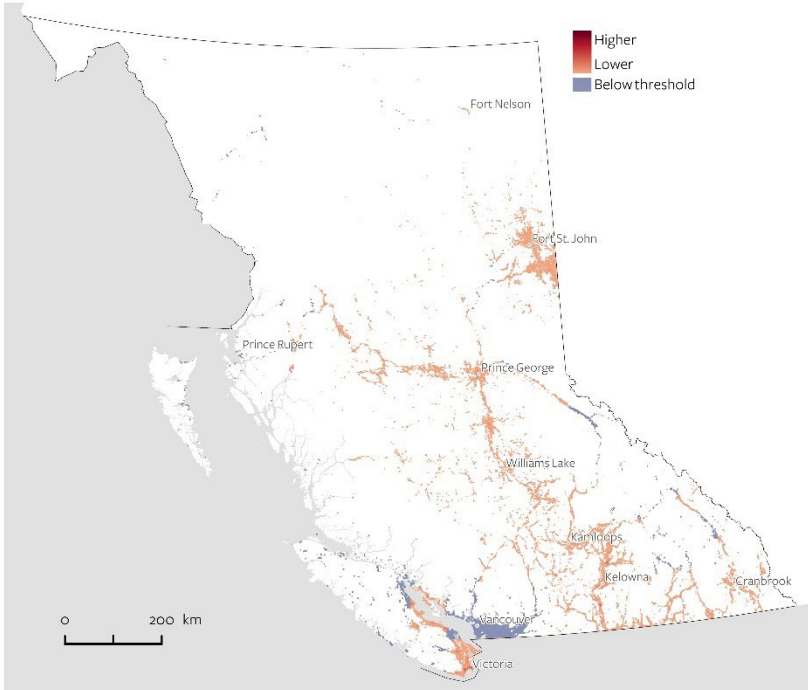


Figure A-8-2 Population densities threatened by a worse 50-year meterological drought by 2041-2070, compared to what they experienced in the same area historically (1950 to 2014).

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.

REFERENCES

Ashford, S.A., & Sitar, N. (2002). "Simplified Method for Evaluating Seismic Stability of Steep Slopes." *Journal of Geotechnical and Geoenvironmental Engineering* 128 (2): 119-128. https://doi.org/10.1061/(ASCE)1090-0241(2002)128:2(119).

Assessment Act. (1996). *Assessment Act of BC (current to April 24, 2024)*. https://www.bclaws.gov.bc.ca/civix/document/id/complete/statreg/96020_01.

BC Wildfire Service (BCWS). (2021). "Provincial Strategic Threat Analysis." Map prepared for Ministry of Forests, Lands, Natural Resources and Rural Development.

BGC Engineering Inc. (2019, March 31). "Flood and Steep Creek Geohazard Risk Prioritization." Final Report Prepared for Regional District of Central Kootenay.

BGC Engineering Inc. (2021, June 4). "Thompson Nicola Regional District Flood Hazard Assessment." Final Report prepared for Fraser Basin Council.

BGC Engineering Inc. (2023, April 24). "Regional Geohazard Risk Assessment." Final Report prepared for Squamish-Lillooet Regional District.

BGC Engineering Inc. (2024, April 19). "Mapping for Floodplain Identification (Stage 1)." Final Report prepared for BC Hydro.

Bray, J.D., & Macedo, J. (2019). "Procedure for Estimating Shear-Induced Seismic Slope Displacement for Shallow Crustal Earthquakes." *Journal of Geotechnical and Geoenvironmental Engineering* 145 (12): 04019106. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002143.

Building Seismic Safety Council (BSSC). (1994). "NEHRP Recommended Provisions for Seismic Regulations for New Buildings, Part 1: Provisions." https://www.nibs.org/page/bssc_1994pubs.

Church, M., & Jakob, M. (2020). What is a debris flood? Water Resources Research. 56(8). https://doi.org/10.1029/2020WR027144

Church, M. (2022). "Steep Headwater Channels." In *Treatise on Geomorphology (Second Edition)*, 841-864. https://doi.org/10.1016/B978-0-12-409548-9.12027-5

Copernicus DEM – Global and European Digital Elevation Model, GLO-30, ESA, Copernicus [Data]. https://doi.org/10.5270/ESA-c5d3d65

Cousineau, J., & Murphy, E. (2022). "Numerical Investigation of Climate Change Effects on Storm Surges and Extreme Waves on Canada's Pacific Coast." *Atmosphere* 13: 311. https://doi.org/10.3390/atmos13020311. Model data provided by Julien Cousineau on April 26, 2024.

Cui, Y., Miller, D., Schiarizza, P., & Diakow. L.J. (2017). "British Columbia Digital Geology [GIS Data]." *British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Open File 2017-8*, 9p. Data version 2019-12-19.

Engineers and Geoscientists British Columbia (EGBC). (2024). “Use and Development of Seismic Microzonation Maps in BC [Guideline].” Version 1.0, May 10.

Environment and Climate Change Canada (ECCC). (2023). “Criteria for Public Weather Alerts – Heat.” https://www.canada.ca/en/environment-climate-change/services/types-weather-forecasts-use/public/criteria-alerts.html#heat. Information retrieved on December 5, 2023.

Federal Emergency Management Agency (FEMA). (2020). “Hazus Earthquake Model Technical Manual.” October. https://www.fema.gov/flood-maps/tools-resources/flood-map-products/hazus/user-technical-manuals

Ferguson, R. (1986). River Loads Underestimated by Rating Curves. Water Resources Research. 22(1):74-76. https://doi.org/10.1029/WR022i001p00074

Geological Survey of Canada (GSC). (2014). “Surficial Geology of Canada [Map].” Scale 1:5,000,000. Surficial Data Model V.2.0 Conversion, Geological Survey of Canada, Canadian Geoscience Map, 195. https://doi.org/10.4095/295462

Hobbs, T., Journeay, J.M., Rao, A.S., Kolaj, M., Martins, L., LeSueur, P., . . . & Chow, W. (2023). “A National Seismic Risk Model for Canada: Methodology and Scientific Basis.” *Earthquake Spectra* 39: 875529302311734. https://doi.org/10.1177/87552930231173446

James, T., Henton, J., Leonard, L., Darlington, A., Forbes, D., & Craymer, M. (2014). “Relative Sea-Level Projections in Canada and the Adjacent Mainland United States.” Open file 7737 (Geological Survey of Canada), Government of Canada, Ottawa, Ontario.

Kendall, M. (1938). “A New Measure of Rank Correlation.” *Biometrika* 30 (1–2): 81–89. doi:10.1093/biomet/30.1-2.81. JSTOR 2332226.

Kolaj, M., Halchuk, S., & Adams, J. (2023). “Sixth-Generation Seismic Hazard Model of Canada: Grid Values of Mean Hazard to Be Used with the 2020 National Building Code of Canada [Data].” *Geological Survey of Canada, Open File 8950* (ver. 1.0), 1 .zip file. https://doi.org/10.4095/331497

Natural Resources Canada. (2022a). “Social Vulnerability to Natural Hazards in Canada.” *Geological Survey of Canada Open File 8892*

Natural Resources Canada. (2022b). “Physical Vulnerability to Natural Hazards in Canada.” *Geological Survey of Canada Open File 8902*

Oregon Department of Geology and Mineral Industries. (2019). “Coseismic Landslide Susceptibility, Liquefaction Susceptibility, and Soil Amplification Class Maps, Clackamas, Columbia, Multnomah, and Washington Counties, Oregon (DOGAMI Open-File Report O-19-09).” https://www.oregongeology.org/pubs/ofr/p-O-19-09.htm

Pacific Climate Impacts Consortium (PCIC). (2024). “Assessing Extreme Heat in a Changing Climate: Analysis and Deliverables for the DCRRA.” Prepared for Ministry of Environment and Climate Resilience, March 12.

Pronk, M., Hooijer, A., Eilander, D. et al. (2024). DeltaDTM: A global coastal digital terrain model. Sci Data 11: 273. https://doi.org/10.1038/s41597-024-03091-9

Santucci de Magistris, F., Lanzano, G., Forte, G., & Fabbrocino, G. (2013). “A Database for PGA Threshold in Liquefaction Occurrence.” *Soil Dynamics and Earthquake Engineering* 54: 17-19. http://dx.doi.org/10.1016/j.soildyn.2013.07.011

Tam, B.Y., Cannon, A.J., & Bonsal, B.R. (2023). “Standardized Precipitation Evapotranspiration Index (SPEI) for Canada: Assessment of Probability Distributions.” *Canadian Water Resources Journal* 48 (3): 283-299. https://doi.org/10.1080/07011784.2023.2183143

VanDine, D.F. (1996). Debris Flow Control Structures for Forest Engineering. BC Ministry of Forests Research Program. Victoria, B.C., Working Paper.

Wald, D.J., Quitoriano, V., Heaton, T.H., & Kanamori, H. (1999). “Relationships between Peak Ground Acceleration, Peak Ground Velocity, and Modified Mercalli Intensity in California.” *Earthquake Spectra* 15 (3): 557-564. https://doi.org/10.1193/1.1586058

Warman, D.J., Kendrick, D.Z., & Mackenzie, J.D. (2018). “Development of a Pipeline Post Seismic Response Screening Process.” *Proceedings of the 2018 12th International Pipeline Conference*, September 24-28, Calgary, Canada.

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)

APPENDIX D
METADATA (PROVIDED UNDER SEPARATE COVER)

APPENDIX E
MAPS AND CHARTS (PROVIDED UNDER SEPARATE COVER)

APPENDIX F
SOFTWARE CODE
(PROVIDED UNDER SEPARATE COVER)

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