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National Feasibility Study for Flood Hazard Modelling and Mapping at a Regional Scale

Environmental Scan Report

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NRCAN

National Feasibility Study for Flood Hazard Modelling and Mapping at a Regional Scale – Environmental Scan Report

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PREPARED BY:

Taylor Fajardo, P.Eng.
Water Resources Engineer, KGS Group

Danker Kolijn, M.Sc., P.Eng.
Senior Coastal Engineer, DHI



For Coastal Engineering

Méven Robin Huiban, M.Sc.
Senior Coastal Scientist, DHI



Andrew Weiss, P.Eng.
Water Resources Engineer, KGS Group

APPROVED BY:

David S. Brown, P.Eng.
Principal, KGS Group

ENGINEERS
GEOSCIENTISTS
MANITOBA

Certificate of Authorization

KGS Group

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List of Abbreviations

1D – One-Dimensional
2D – Two-Dimensional
AEP – Annual Exceedance Probabilities
AI – Artificial Intelligence
ANUSPLIN – Australian National University Spline
AR – Assessment Reports
AR6 – Sixth Assessment Report
BLE – Base Level Engineering
CCMEO – Canada Centre for Mapping and Earth Observation
CHS – Canadian Hydrographic Service
CaMa Flood – Catchment-based Macro-scale Floodplain
CaPA – Canadian Precipitation Analysis
CBCL – CBCL Limited
COWCLIP – Coordinated Ocean Wave Climate Project
DEM – Digital Elevation Model
ECCC – Environment and Climate Change Canada
EVA – Extreme Value Analysis
FEMA – Federal Emergency Management Agency
FOA – First Order Approximation
FCL – Flood Construction Levels
FHIMP – Flood Hazard Identification and Mapping Program
GEM-Hydro – Global Environmental Multiscale Hydrological Modeling Platform
GIS – Geographic Information System
HAND – Height Above Nearest Drainage
HEC-HMS – Hydrologic Engineering Center's Hydrologic Modeling System
HEC-RAS – Hydrologic Engineering Center's River Analysis System
HRM – Halifax Regional Municipality
IDF – Intensity-Duration-Frequency
IPCC – Intergovernmental Panel on Climate Change
LiDAR – Light Detection and Ranging
LSAE – Large Scale Automated Engineering
MELCCFP – Ministère de l'Environnement, de la Lutte contre les Changements Climatiques, de la Faune et des Parcs
MESH – Modélisation Environmentale Communautaire - Surface and Hydrology
ML – Machine Learning
MRDEM – Medium Resolution Digital Elevation Model
NOAA – National Oceanic and Atmospheric Administration
NTHMP – National Tsunami Hazard Mitigation Program
NRCan – Natural Resources Canada
NONNA – Non-navigational

SSP – Shread Socioeconomic Pathways
SWORD – SWOT River Database
SWOT – Surface Water and Ocean Topography
USACE – United States Army Corps of Engineers
UNEP – United Nations Environment Programme
UPEI – University of Prince Edward Island (UPEI)
USGS – United States Geological Survey
WMO – World Meteorological Organization
XAI – Explainable Artificial Intelligence

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1.0 INTRODUCTION

1.1 Background

In recent years Canada has experienced large-scale regional flooding, exposing Canadians to severe public safety risks and hazards, while having profound impacts on economic activity and the natural and built environment. Flood hazards are not limited to pluvial and fluvial events, and frequently occur at a regional scale in coastal environments on the Great Lakes and along Canada's coastal communities in the Atlantic, Arctic, and Pacific. Recent climate disasters, such as Hurricane Fiona and the 2021 atmospheric river events in British Columbia that resulted in widespread flooding, have illustrated the role that a changing climate has played to enhance the risk and exposure of the Canadian economy, public, and environment to regional flood hazards.

Climate change is projected to exacerbate flood risk throughout Canada with patterns of increased precipitation intensity, rising sea levels, reductions in sea-ice to protect shorelines from winter waves, altered hydrology, prolonged droughts, and compound flooding, to name but a few. These factors combine to overwhelm drainage systems, cause surface flooding, and inundate coastal and low-lying urban areas. These challenges must be studied at both local and regional levels to identify critical flood risk and hazards. While local watershed scale flood hazard studies are relatively established in urbanized areas throughout Canada, regional applications are not as common, especially when compared to other countries.

To help Canadians better prepare for future floods in our ever-changing climate, Natural Resources Canada (NRCan) launched the Flood Hazard Identification and Mapping Program (FHIMP) in 2021 in collaboration with Environment and Climate Change Canada (ECCC) and Public Safety Canada. This program encouraged Provinces and Territories to undertake flood mapping projects by providing a portion of federal funding on eligible projects. Local governments, as well as Provincial and Territorial governments often prioritize their resources on the areas of high flood risk, which leaves large areas of Canada that are less prone to flooding left without flood risk information.

NRCan would like to address this data gap where flood risk is lower or in areas where it may not be financially or technically feasible to develop detailed flood hazard maps by developing an efficient and robust flood hazard mapping methodology that can be employed at a large geographic scale ranging in size from the hydrologic and hydraulic analysis of a single watershed to up to provincial-scale analyses. While detailed flood hazard mapping studies provide a very high level of detail and the lowest uncertainty in the resulting flood hazard extents, these studies are very resource intensive, requiring significant costs, time, and technical expertise. Accordingly, given the practical limitations of implementing detailed flood hazard mapping on a large scale, a coarser approach applied to a large geographic scale can be appropriate for a number of use cases where such a high level of detail is not required or warranted.

1.2 What is Regional Flood Modelling?

A regional-scale approach to flood hazard modelling and mapping would leverage expert knowledge and understanding of the flood mechanisms at play within the study area to best represent the potentially flood

affected areas and leverage local data to calibrate and validate the models and maps as best as possible. In this regard, regional-scale flood hazard modelling differs from global-scale modelling, where calibration and validation may not consider local and regional features, or where there may not be sufficient consideration for key flooding mechanisms. Conversely, regional-scale modelling and mapping differs from detailed flood studies by leveraging a number of simplifications, such as coarser input data, models, or methods, to facilitate the implementation of the approach to a much broader scale. Accordingly, regional scale modelling and mapping serves to bridge the gap between coarse, global scale modelling and mapping products, and detailed flood hazard studies that are limited in geographic scope. The three tiers of flood hazard modelling can be further defined as:

- **Detailed engineering flood hazard modelling:** Engineering-level hydrological and hydraulic modeling using high-resolution data inputs, detailed information on bathymetry and hydraulic structures, detailed hydrological and meteorological data, and extensive model calibration and validation. Implemented at a small geographic scale for a local area for detailed regulatory land use planning, infrastructure and site-level assessments, and detailed hazard assessments. Detailed engineering flood hazard modelling corresponds to the highest technical standard for currently producing flood hazard maps in Canada.
- **Regional flood hazard modelling:** Regional-scale hydrological and hydraulic modelling using medium to high-resolution data inputs, limited information on bathymetry and hydraulic structures, and some degree of model calibration and validation. This level of modelling and mapping can also leverage Geographic Information System (GIS)-based or hydro-geomorphological approaches. Regional flood hazard modelling is implemented at a regional geographic scale (i.e. one or multiple watersheds) for hazard screening and prioritization, public awareness, emergency response planning, preliminary land-use planning, and high-level hazard assessment. Regional flood hazard modelling aims to produce approximate flood hazard maps to fill in gaps between detailed engineering flood hazard maps.
- **Global flood hazard modelling:** High-level analysis using low to medium-resolution data inputs, no information on bathymetry and hydraulic structures, large-scale data or broad assumptions on hydrology and very limited model calibration and validation. Implemented at a large scale (i.e., global coverage, national coverage, multiple provinces, etc.) for hazard screening and prioritization, public awareness, emergency response planning, preliminary land-use planning, and high-level hazard assessment. While sometimes including local details and features, global flood hazard modelling aims to provide a coarse estimate of flood hazard risk, which is not site specific.

The methods used to develop these regional-scale models and maps could range from coarser GIS-based approaches, such as the height above nearest drainage (HAND) method, to deterministic approaches such as hydrologic and hydraulic modelling, as implemented in detailed flood hazard mapping studies. However, given the broader geographic scale and anticipated coarser datasets used in the development of regional-scale flood hazard models and maps, and in turn the increased uncertainty in the ultimate flood extents, the appropriate use cases for regional-scale flood hazard models and maps differs from those associated with detailed flood hazard mapping studies. These use cases, as well as potential approaches, associated with global-scale, regional-scale, and detailed flood hazard modelling and mapping products are summarized in Table 1.

TABLE 1: GEOGRAPHIC SCALES OF FLOOD HAZARD MAPPING

Level	Description	Geographical scale	Potential use cases
Level 1 **Global**	• High-level analysis using low- to medium-resolution Digital Elevation Model (DEM), no data on bathymetry and hydraulic structures, large-scale data or broad assumptions on hydrology • May include local details or features, but generally include coarser approaches • Remote sensing or machine-learning-based susceptibility estimates	Large (ex. national coverage, multiple provinces)	• Hazard screening and prioritization • Public awareness • Emergency response planning • Preliminary land use planning (i.e. screening level) • High-level risk assessment
Level 2 **Regional**	• Hydrological and hydraulic modelling with some data on bathymetry and structures, regional hydrological methods • GIS-based (ex. HAND), or hydro-geomorphological approaches with medium or high-resolution DEM • Some degree of validation and calibration with historical flood data	Regional area (ex. one or multiple watersheds, provincial coverage)	
Level 3 **Detailed Engineering**	• Engineering-level hydrological and hydraulic modelling using high-resolution DEM, detailed bathymetry and structures, detailed hydrological and meteorological data • Detailed validation and calibration of model parameters	Local area	• Detailed regulatory land use planning (i.e. by-laws, zoning, etc.) • Infrastructure and site-level assessments • Detailed risk assessment

To support flood mapping practitioners throughout Canada, NRCan has retained KGS and DHI to develop a set of technical guidance documents and best practices for the execution of regional-level flood hazard modelling and mapping. To better inform those guidelines, KGS and DHI have completed research into ongoing and planned regional flood hazard modelling and mapping programs, and have engaged with a number of experts from academia, government, and the consulting industry to better understand key challenges and limitations associated with regional flood hazard modelling and mapping.

1.3 Objective and Scope

The primary objective of the environmental scan is to review and document the current state of play regarding regional flood hazard modelling and mapping throughout Canada, and to synthesize the experience and knowledge of experts from government, academia, and industry to support the development of technical guidance documents and best practices. In particular, the focus of the environmental scan served to highlight knowledge, challenges, and limitations related to:

- Expert experience in the execution of regional flood hazard modelling and mapping.
- The overall appropriateness of regional scale modelling and mapping, and its potential uses.
- The availability and quality of data that can be used to support regional scale modelling and mapping.
- Remote sensing and earth observation data.
- Advanced modelling techniques, as well as the different levels of complexity considered in regional flood modelling.
- Compound flooding.
- Climate change considerations.
- Artificial intelligence and machine learning.
- Future research that should be pursued to better support regional flood hazard modelling.

An overview of the typical flood mechanisms considered in flood hazard modelling and mapping in Canada, as well as potential approaches to address those causes from a regional perspective, are summarized in Section 2.0. The current state of play of regional flood hazard modelling and mapping is summarized in Section 3.0, with select projects described in further detail in Section 4.0. A synthesis of the expert engagement completed by KGS and DHI is provided in Section 5.0, with key considerations that should be included in guidance documents for regional flood hazard modelling and mapping provided in Section 6.0.

2.0 REGIONAL FLOOD MODELLING APPROACHES

2.1 Overview

Flooding throughout Canada can be caused by a broad number of primary causes, owing to Canada's extensive and varied geography and climates. The varied nature of flooding throughout Canada is further complicated by the potential for the combination of different flood mechanisms as part of the same flood event, known as compound flooding. Flooding due to the failure of dams or dikes was not considered as part of this project. At a high level, the typical causes of flooding throughout Canada include:

- ***Fluvial flooding,*** where high flow on a waterway exceeds the conveyance of the waterway, resulting in flooding extending into the floodplain. Fluvial flooding can also occur on lakes, where inflows raise water levels to the point where they flood adjacent land. Fluvial flooding can result from a number of causes, including abnormal snowpack, fast snowpack melt, rain-on-snow events, and heavy precipitation.
- ***Pluvial flooding,*** where extreme rainfall causes overland flooding separate from a waterway. This can include flooding in an urban setting, where the storm sewer system is overwhelmed by the rainfall, or in a rural setting where the rainfall exceeds the capacity of the ground and vegetation to absorb or store the water. Pluvial flooding can also trigger flash flood events.
- ***Coastal flooding***, where coastal and lakefront areas are flooded by storm surge, wave setup, wave runup, or a combination of all of the above. Coastal flooding along the Atlantic, Arctic, and Pacific coasts can further be exacerbated by the occurrence of the flooding concurrently with high tide conditions.
- ***Ice jam flooding***, where the accumulation of ice floes results in the partial blockage of a waterway, significantly reducing the conveyance, and increasing water level upstream of the ice jam location. Ice jam flooding is typically localized to the area near the ice jam. However, ice jams can occur at multiple locations during the freeze-up or breakup of ice along a waterway, resulting in multiple ice jams during one flood event.
- ***Tsunamis***, where flooding is triggered by the sudden displacement of a large volume of water, typically due to landslides or earthquakes, resulting in very long wavelength waves that can propagate very far from the source of the water displacement. As the wave enters shallow water, the velocity of the wave is reduced, and the amplitude (i.e. height) of the wave increases, resulting in significant flooding along coastal zones.
- ***Groundwater flooding***, where groundwater levels become excessively high, resulting in flooding of any subterranean infrastructure, such as excavated basements.
- ***Compound flooding***, where multiple sources of flooding occur in combination. As an example, this can include pluvial or fluvial flooding occurring at the same time as coastal flooding, as a post-tropical storm brings both heavy or persistent precipitation, resulting in pluvial and / or fluvial flooding, as well as high coastal water levels due to storm surge and wave runup.

Typical approaches to modelling the above flood mechanisms are described in the following subsections, as well as the overall appropriateness of considering each mechanism from a regional perspective.

2.2 Fluvial Flooding

Fluvial flooding occurs when water levels on a river, stream, or lake exceed the capacity of the waterbody, resulting in flooding in the adjacent floodplain. On rivers and streams, fluvial flooding occurs when the flows on the waterway exceed conveyance (i.e. the capacity of the waterway to move water). On lake shorelines, flooding can be caused by high inflows exceeding the outlet capacity of the lakes, raising lake levels to the point where adjacent land is flooded. There are a number of causes for high flows on rivers and streams that result in flooding, which include:

- Heavy rainfall, which can include both synoptic events, such as post-tropical storms, or more localized heavy rainfall, such as atmospheric rivers.
- Rapid snowmelt.
- Abnormally deep snowpack.
- Rain-on-snow events, which result in both higher than normal rainfall runoff and accelerated melting of the snowpack.

Modelling methods for mapping flood hazards associated with fluvial flooding are well established in Canada, with strong experience in the consulting engineering industry in the execution of flood hazard modelling and mapping studies. This experience is further supported by guidance documents from Natural Resources Canada, including in particular the Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation (NRCan, 2023). In short, the modelling methods used for flood hazard mapping include:

- The definition of hydrologic inputs to hydraulic modelling representative of events of interest, such as specified return period flood events, a specific meteorological event, or a historical flood of record. The hydrologic inputs can be defined by statistical analyses based on available hydrometric data, or by hydrological modelling, where the model is calibrated to historical flood events and used to simulate a design storm. For statistical analyses, if data is available at a discrete location, the duration of the record would have to be sufficiently long to estimate events with an annual exceedance probability being considered for flood hazard modelling and mapping.
- A significant portion of rivers throughout Canada are affected by flow regulation due to hydroelectric generation, flood protection, and irrigation, and it is critical to understand and account for the effects of regulation on historical recorded flows on those instances. This is typically addressed by reconstructing the natural flow record considering operational data associated with the regulation structures, such as historical water levels, outflows, and stage-storage curves, in a process known as flow naturalization. Flow naturalization should be completed where possible to understand the impacts associated with flow regulation relative to the naturalized flows.
- An analysis of the anticipated impacts due to climate change and future land use changes is completed to define a set of hydrologic inputs considering those impacts.
- A hydraulic model is developed based on available topographic and bathymetric information, hydraulic structure data, and anticipated roughness coefficients in the study area. The model can be one-dimensional (1D), two-dimensional (2D), or coupled 1D/2D. The model is calibrated to historical flood events, and is then used to simulate the flows defined by the hydrologic analysis. Results from the hydraulic model are post-processed in a GIS environment to develop flood hazard information.

The above methodology is well suited to a regional setting, although there are a number of simplifications, assumptions, and considerations to enable the application of the methodology to large geographic extents. These include:

- The best available topographic data should be used, such as Light Detection and Ranging (LiDAR) information, when possible. Ideally, the full model domain will leverage LiDAR data, but lower resolution topographic data can be used, albeit with a lowered expectation of the ultimate accuracy of the flood hazard extents.
- Lower model resolution is required to manage the computational requirements of implementing a regional hydraulic model. Advanced modelling techniques, such as serialization of model domains and simulations, can facilitate a higher model resolution, but it will still be lower than those considered in detailed flood hazard mapping studies.
- The integration of certain hydraulic infrastructure into the model, such as culvert and bridge crossings, must be simplified to ensure that the development of the model is feasible. This can include either a simplified representation of minor structures, such as including modifications to the Digital Elevation Model (DEM) to represent the conveyance of culverts and small bridges, or only considering major river crossings in the development of the model. These simplifications will impact the overall accuracy of the resulting flood hazard extents, as well as appropriate use cases.
- Given that flood protection infrastructure, such as dikes, dams, and floodwalls protect a significant number of Canadian communities, it is critical to ensure that flood protection infrastructure is accurately represented the hydraulic model. The basis for defining the flood protection infrastructure should be defined in the model based on the best available information, such as LiDAR, design drawings, or field survey data.
- River bathymetry is sometimes neglected on shallow rivers where less water is conveyed through the main channel. For deeper rivers, if the model topography is defined by LiDAR, river bathymetry can be estimated based on recorded flows on major watercourses. Alternatively, design flows can be reduced by the estimated flows at the time of LiDAR capture to account for channel capacity below the water surface in the LiDAR data.
- Calibration and validation data will likely be limited, and thus additional strategies to validate the model results should be considered, such as comparisons of simulated flood extents to those captured by remote sensing satellites, optical satellites, or aerial imagery for known historical floods, to understand the accuracy associated with the flood hazard extents.
- The use of existing detailed hydraulic models and/or their results should be considered either as downstream boundary conditions or as benchmarking comparison points for regional models.

In addition to the use of numerical models to evaluate fluvial flood hazards, GIS-based approaches, such as the HAND (i.e. height above nearest drainage) method can be implemented to define a high-level delineation of flood hazards. These methods do not consider the physical processes at play, but can be implemented with limited supporting information. Furthermore, there is some capacity to calibrate or validate the delineated flood hazard zones to historical flood extents, thus increasing the confidence of the delineated hazard extents where calibration and validation data supports the delineated extent. However, given the simplifications associated with these methods, it should be understood that there is generally a higher level of uncertainty associated with these methods, and as such they are not appropriate for all use cases.

Nonetheless, these GIS-based methods can be appropriate for defining high-level flood hazard extents in areas with limited information, where model-based estimation of flood hazard may not be technically feasible.

2.3 Pluvial Flooding

Pluvial flooding occurs when rainfall exceeds the capacity of the ground, vegetation, and stormwater infrastructure to absorb the rainfall. Typically, pluvial flooding can result from large, synoptic weather events, such as post-tropical depressions, convective storms, atmospheric rivers, or sustained moderate precipitation.

Modelling methods for pluvial flooding within Canada are well established, although typically implemented at smaller scales, such as throughout a city or small watershed, allowing for any drainage infrastructure to be accurately represented in the model. These models are typically used for the design of stormwater infrastructure, as the mapping of pluvial flood hazards is relatively uncommon in Canada. In short, the modelling methods used for pluvial flood assessments includes:

- The definition of design storms, including the definition of hyetographs and the spatial extents of those hyetographs. These can include synthetic storms, such as those defined by the Alternating Block method, or historical rainfall events, such as the rainfall associated with Hurricane Hazel, as used in Ontario.
- A rainfall-runoff model is developed to represent the hydrological processes associated with rainfall runoff, which can include the infiltration capacity of the ground surface, as well as the change in that infiltration capacity over time, depression storage, evapotranspiration, abstractions due to stormwater infrastructure, and the conveyance of the runoff along the ground surface.
- The design storm is then simulated over the rainfall-runoff model domain to assess overland flooding and flow rates at key locations throughout the model. The rainfall-runoff model is generally calibrated to historical rainfall events considering available rainfall and flow data.

The above methodology can be adapted to facilitate pluvial flood hazard modelling and mapping in a regional setting, although similar to fluvial flood modelling, there are a number of simplifications, assumptions, and considerations that are required to enable the application of the pluvial flood modelling methodology to large geographic extents. These include:

- The development of representative storm events over the full model domain. These can include simulations of available historical rainfall data, such as gridded precipitation from the Canadian Precipitation Analysis (CaPA), design storms applied over the model domain or interpolated between climate stations, or stochastic weather generation, such as the Stochastic Storm Transposition method developed by the U.S. Army Corps of Engineers. However, care should be taken regarding the duration of the record used to estimate annual exceedance probability being considered for flood hazard modelling and mapping.
- Hydraulic infrastructure must be simplified to ensure that model development is feasible. Simplifications can include either a simplified representation of minor structures, such as including modifications to the Digital Elevation Model (DEM) to represent the conveyance of culverts and small bridges, or only

considering major hydraulic infrastructure in model development. These simplifications will impact the overall accuracy of the resulting flood hazard extents, as well as appropriate use cases.

- The precise representation of stormwater infrastructure may not be feasible to integrate into rainfall-runoff models in a regional context. Instead, rainfall in urban areas with stormwater infrastructure can be reduced by the anticipated design rainfall event associated with the stormwater infrastructure. It should be noted that this is an active area of research, and further guidance will likely be available in the near-future regarding appropriate assumptions regarding different aspects associated with stormwater infrastructure, such as the storm intensity and timing, urban density, and their impacts on runoff.
- Depending on the selected model, it may not be feasible or possible to integrate all of the typical aspects considered in rainfall-runoff models, such as transpiration or evaporation. In those instances, it would be necessary to adjust either rainfall or infiltration parameters to represent those aspects.

More recent advancements in pluvial flood hazard modelling considers the representation of rainfall processes within traditional hydraulic models. Specifically, this approach represents key pluvial processes in a typical fluvial modelling environment, including gridded precipitation, infiltration, and runoff processes, and can serve as a more representative approach to defining fluvial flood hazards, albeit at a considerably higher computational cost. Pluvial flooding is a significant driver of flood risk in urban areas and is anticipated to be most significantly impacted by climate change. Furthermore, the mapping of pluvial flood hazards is considerably less advanced than fluvial and coastal flood hazards. Accordingly, consideration should be given to integrating rain-on-grid processes in the development of regional flood hazard models at select areas of interest, such as populated areas or areas with a history of pluvial flood risk. Simplifying assumptions required to implement this method would be similar to those defined for traditional rainfall-runoff modelling.

Similar to fluvial flood modelling, calibration and validation data will likely be limited in a regional context, and thus additional strategies to validate the model results should be considered, such as comparisons of simulated flood extents anecdotal information, remote sensing inundation extents, or aerial imagery of flood extents for known historical floods, to understand the accuracy associated with the flood hazard extents.

2.4 Coastal Flooding

With the longest coastline in the world, Canada has considerable exposure to coastal hazards and associated flooding. Canada is surrounded by three of the five greats oceans; the Atlantic, Arctic, and Pacific, each with unique characteristics and features which expose Canadians to variable degrees of coastal flood risks and hazards.

In addition to these oceanic coasts, large lake systems can also be regarded as coastal environments for flooding when they generate hazards associated with varying lake levels, storm surges, and high wave energy, which can adversely affect the built and natural environment. The existence of such processes in lakes environment is driven by the lake's exposure to climatic effects and other factors such as its size, depth, shape and orientation. The Great Lakes, as well as other significant lake systems such as Lake Winnipeg, Great Slave Lake, and Great Bear Lake, are notable examples of such systems.

Together, these systems present a complex suite of flood hazards to interpret at a regional scale. The following flood risks are associated with coastal flooding:

- **In ocean environments,** coastal flooding is associated with storm surges from large scale seasonal storms, tropical storms and hurricanes, wave processes such as run-up and overtopping, combined high tide with storm surge and wave exposure, long-term sea level rise, and extraordinary events such as tsunamis.
- **On inland lakes,** high lake levels can create variable flood risk from one year to the next. Although the Great Lakes water levels are regulated, sustained high water levels together with reduced ice coverage has increased flood risk in recent years, with significant shoreline damage observed along Lake Erie and Lake Ontario in recent years. Shallow lake systems can also experience significant seiching and set-up, increasing flood risk locally along shoreline exposed by prevailing and sustained winds. Wave hazards in large lake systems can be significant, with wave heights frequently exceeding thresholds typically associated with oceanographic environments, and thus these conditions should not be underestimated.
- **In arctic regions,** reductions in sea ice and loss of permafrost along open coasts may increase erosion rates, enhancing exposure to coastal hazards and flooding.
- **In all environments**, extraordinary geohazards such as landslides or submarine landslides can trigger localized tsunamis, which may pose flood risks and hazards. Additionally, significant changes to nearshore morphology, primarily driven by erosion, can result in greater coastal flood risk due to higher degrees of exposure from waves or storm surge effects. Structural interventions can also introduce unintended consequences, which could exacerbate coastal flood risks. Loss of shoreline vegetation, marsh systems and other natural features and environment can result in a changing foreshore profile more conducive to coastal flooding. Compound flooding in estuaries with significant freshwater contributions (run-off) together with high tides and storm surge, can enhance coastal flood risk within estuaries.

The processes listed above can be investigated, modelled and interpreted at various scales and levels of detail. However, only some of the processes listed are appropriate for consideration in assessing regional coastal flood hazards along the less populated and more isolated regions of Canada. It is proposed that, at a regional scale, the following processes be considered for coastal flood hazard modelling:

- Storm surge and joint probability of surge and high tidal levels.
- Lake seiching and set-up.
- Wave hazards including wave run-up and set-up.
- Tsunamis, for coasts where exposure and risk are identified.
- Future flood hazards associated with sea level rise and secondary impacts from a loss of sea ice or changes to storm intensity and frequency.

Flood hazards associated with changing shoreline features and profiles due to erosion, loss of shoreline vegetation and habitat, permafrost loss, compound flooding in estuaries (with the exception of very large systems such as the Fraser River and Mackenzie Delta systems), and geohazards such as local tidal waves generated by landslides, should be considered as local processes, which are more challenging to characterize and investigate at regional scale. Thus, it is recommended to identify these processes as potential contributors to coastal flood hazards in a regional assessment, and to investigate these further in greater details when conducting a site-specific or detailed coastal flood hazard investigation.

Regional coastal flood hazard modelling requires a large-scale interpretation and understanding of oceanographic and lake-wide hydrodynamics and waves. Traditionally, assessments of these processes have been completed using the analysis of historical data records at water level or wave gauging stations. Throughout Canada in both lakes and along coastlines these records are incomplete, occasionally unreliable, and often only available near larger urban coastal communities. This poses a significant challenge when looking for data to use in regional flood hazard assessments for less developed regions or territories. Additionally, if data is available at a discrete location, the duration of the record would have to be sufficiently long to be reliably used to predict events with a return period or annual exceedance probability, which is suitable for coastal flood hazard studies (i.e. in the order of 100-years or 1% AEP). According to USACE (CEM, 2006), when performing an Extreme Value Analysis (EVA) to derive flood hazard mapping conditions, extrapolation beyond three times the data record length should be avoided if possible[1]. Therefore, it is often challenging to predict coastal storm surge and wave effects responsible for coastal flooding in regional or rural communities due to:

- A lack of regional data at sufficient resolution to infer regional levels of coastal hazard exposure.
- The regional and site-specific nature of storm surge gradients and wave effects that cannot be described by distant data sources.
- Water level data records that are too short, outdated or unreliable to derive return values for surge events or understanding of joint tidal and storm surge impacts locally at a site of interest.

Regionally, extreme water levels can be interpreted using 2D numerical modelling tools which generate a long-term hindcast (i.e. > 50-years) of atmospheric residuals or total water levels, which incorporate all storm driven events over the simulation period. Statistics can then be used to derive the variable AEP of the residual or total water level along the regional shoreline of interest. It is important that such models are calibrated and validated to long-term observations. Such long-term hindcast products are widely available for the Great Lakes and along the East and West coast of Canada from American and Canadian Federal agencies and research institutions. In tidal environments, it is generally recommended to consider total water levels (combination of tide and storm surge) when assessing the AEP of a coastal flood water level. Alternatively, the surge from individual events, or synthetic storm events, can be simulated where the target water level has a known AEP, using nearby statistics from observations or another hindcast product. This approach is particularly relevant when assessing storm surge associated with tropical storms, hurricanes or cyclones, which often requires dedicated modelling efforts. For example, the AEP of storm surge greater than 2% along the East Coast is frequently assessed using a large ensemble of hurricane models, instead of continuous metocean hindcast models using a regional meteorological hindcast product as forcing.

Wave hazards are particularly challenging to interpret at a regional scale, due to the site-specific nature of wave interaction with the shoreline and the lack of modelling tools and methods which can interpret wave transformation along a shoreline reach over large distances. 1D profile-based modelling methods can interpret wave effects at discrete locations. However, these methods can be insufficient to describe flood mechanisms associated with more complex wave processes such as overtopping, pooling and ponding over

[1] ISO 19901-1 (ISO 2005) recommends to not use return periods more than a factor of four beyond the length of the data set when deriving return values for design of coastal structures.

complex coastal topographies. Small changes in exposure, bathymetry, orientation and foreshore profile, presence of coastal infrastructure and hinterland configuration, can result in considerable variation in wave hazards and associated flooding over small distances. Alternatively, 2D modelling tools are often constrained to domains no more than a few kilometers in length. This makes a comprehensive regional wave hazard assessment often impractical over very large distances such as those required for a regional assessment. Instead, it is recommended to use a combination of numerical modelling methods and tools to assess shoreline exposure and hazard to prevailing wave conditions. Wave energy gradients along shorelines can be used to investigate areas which can experience higher wave energy and exposure, relative to more sheltered sections of shoreline. If required, site-specific wave hazards and exposure can be incorporated into regional assessments at selected locations of interest using empirical methods or 1D modelling tools. Wave hazards should be considered selectively and interpreted at priority sites only for mapping purposes. Coastal flood hazards associated with Climate Change are addressed in Section 2.7.

2.5 Additional Flood Mechanisms

2.5.1 TSUNAMIS

Tsunamis originate primarily from underwater seismic activity, including seismic ruptures from earthquakes, volcanic eruptions, or submarine landslides. When these events occur, large volumes of water are displaced in a relatively short period of time, creating a series of powerful waves that propagate in all directions and can travel across entire ocean basins, reach distant coastlines and inflict catastrophic damage upon coastal regions. Tsunamis are inherently a regional process, as they generally impact large areas. Additionally, landslide triggered tsunami can occur in lakes, fjords, inlets, and rivers which affect smaller sections of the coastlines.

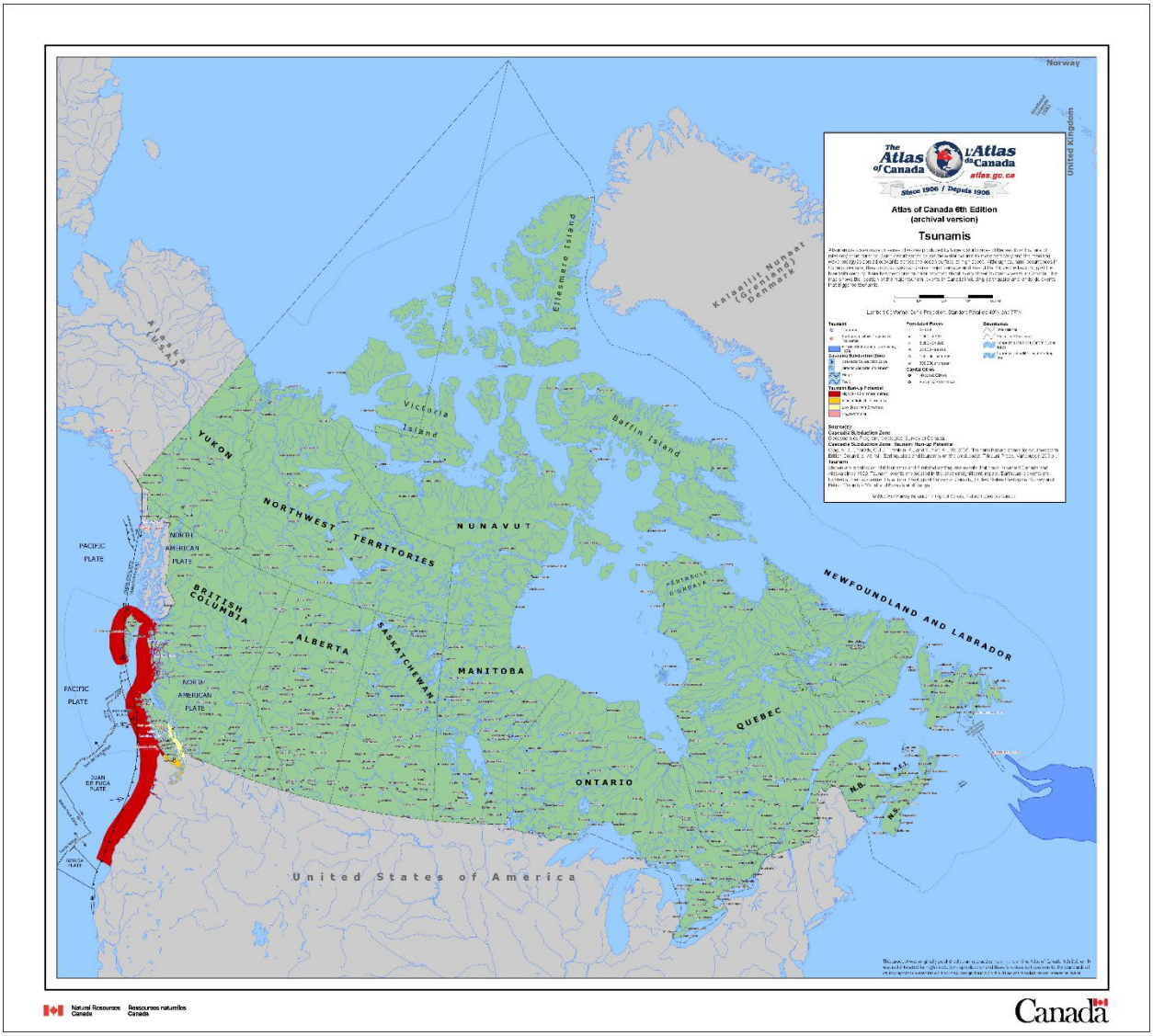
In Canada, tsunami occurrences have been observed on both the Pacific and Atlantic shores of Canada, with a higher frequency on the Pacific side. Figure 1 provides an overview of the locations of historical major tsunami events along Canadian coastlines (NRCan, 2009), including those triggered by earthquake and landslide events. The Pacific coast lies within the seismic “Ring of Fire,” characterized by active continental margins encircling the Pacific basin, leading to a heightened risk of tsunamis compared to the Atlantic Ocean and Arctic Ocean. However, Canada’s East coast has experienced major tsunamis, such as the 1917 tsunami in Halifax Harbour that was triggered by a catastrophic explosion on a munitions ship, as well as the tsunami along the southern coastline of Newfoundland in 1929, which indicates that the risk exists in Newfoundland and Nova Scotia (Clague et al., 2003).

In British Columbia, tsunamis have impacted the province with varying magnitudes, where waves range from a few centimeters, up to several meters. Flood hazards associated with tsunamis are generally well studied along Canada’s west coast, and a strong body of literature, research, mapping efforts, and studies is publicly available to characterize tsunami hazards.

If detailed regional understanding of tsunami hazards is required, specialized regional tsunami modelling tools such as FUNWAVE-TVD can be applied. In general, flood hazard modelling of tsunamis should be conducted using the internationally recognized US National Tsunami Hazard Mitigation Program (NTHMP) guidelines. The NTHMP program is a federal-state partnership, founded by the National Oceanic and Atmospheric Administration (NOAA), whose objective is to plan for and reduce tsunami risk to US coastal

communities. The NTHMP are often applied in Canada and internationally, as they are recognized as best practice. It is important to note that for tsunami modelling, the selection of the tsunami source and magnitude often requires input and interpretation from a seismic expert, who specializes in tsunami dynamics.

FIGURE 1: OVERVIEW OF TSUNAMI RISK ALONG CANADIAN COASTLINES (NRCAN, 2009)



2.5.2 ICE JAMS

Ice jam flooding occurs when features in a river geometry, such as constrictions or sharp bends, lead to the lodgment and accumulation of ice pans, significantly blocking the river conveyance. Ice jamming typically occurs during either the freeze-up period or breakup periods on rivers, although mid-winter ice jam events can also occur. Freeze-up jams typically occur when frazil ice pans lodge and accumulate at the leading edge

of the lodgment, while breakup ice jams occur when ice that has been dislodged, either by thermal processes or mechanical breakup caused by increasing spring flows, lodges and begins accumulating upstream of the lodgment. Mid-winter jams can result from mid-winter increases in flow that can break up the floating ice cover, or dislodge it from the riverbanks, allowing it to travel downstream and potentially jam.

Ice jam flooding is typically evaluated using hydraulic modelling software capable of simulating ice jam processes, such as frazil ice generation, ice accumulation, and the resulting hydraulic conditions associated with the jam. These models can be implemented deterministically, where assumed ice conditions are integrated into the model, or stochastically, where a Monte Carlo analysis is implemented to evaluate the potential range of ice jam conditions. Ice jam modelling requires bathymetric data for the river being modelled to accurately represent the hydraulic conditions associated with ice jamming, as well as a detailed understanding of the various factors that contribute to ice jamming, such as potential jam locations, ice pan thicknesses and strengths, and the volume of ice available to form a jam.

Ice jamming is a highly dynamic and complex process, and is inherently localized to potential jam locations, requiring detailed information at the location of potential ice jams. Accordingly, addressing ice jam flooding at a regional scale is not practical, as it requires a highly detailed evaluation of a given waterway.

2.5.3 GROUNDWATER

Groundwater flooding can occur when the water table rises above minimum basement grade elevations and is able to enter buildings through seepage and / or cracks in foundations. The high water table can be due to a number of processes, including extreme and / or long-duration rainfall events, the bypassing of groundwater flow around typical flood defenses, groundwater rise due to reductions in groundwater loss, such as changes to pumping regimes, and underground structures that block groundwater flow.

Limited, if any, modelling of groundwater flooding has been completed in Canada from a flood hazard mapping perspective. Groundwater modelling requires a detailed understanding of the subsurface conditions, such as soil types, layer thicknesses, and hydraulic conductivity associated with those layers, as well as groundwater monitoring data to calibrate and validate those models. The Canada1Water project is a large-scale project which developed a transboundary model covering all Canadian watersheds. The model was developed using HydroGeoSphere, which is an integrated, fully coupled surface-groundwater model. The model was developed at a large scale and has been simulated to evaluate impacts of climate change on Canada's water resources.

Given the detailed subsurface information that is required to complete groundwater modelling, as well as the highly localized nature of the flood potential, groundwater flooding is not considered to be suitable for evaluation from a regional-scale perspective.

2.6 Compound Flooding

Compound flooding is the process where two or more flood mechanisms occur during the same flood event, such as fluvial flooding and coastal flooding occurring due to the passage of a post-tropical storm. Compound flooding can occur due to statistically independent or dependent processes, and as such it is necessary to complete analyses of the joint probability of those processes. For statistically independent processes, the combined probability of the event can be defined as the product of the probability of each individual event,

and as such it is necessary to investigate the various possible combinations of those probabilities to find the most conservative combination. Alternatively, a Monte Carlo analysis can be completed to define a synthetic set of flood events to better define the sensitivity of each flood process on the overall frequency distribution of flood events.

For statistically dependent processes, different assumptions can be implemented depending on the level of dependence between flood mechanisms. For flood mechanisms that are strongly correlated, the return period associated with each individual flood mechanism can be assumed to match the return period of the overall flood. For weakly correlated flood processes, the relationship can be simplified to assuming that the flood mechanisms are statistically independent. For moderately correlated flood mechanisms, multivariate analysis techniques, such as copula modeling, can capture partial dependency and provide an accurate representation of the joint probabilities and interaction between flood mechanisms.

Some guidance on joint probability analyses is provided in the Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation. However, this guidance is generally focussed on lakeshore flooding, and the relationship between static flood levels, storm surge, and waves. Limited guidance is provided for other potentially dependent flood mechanisms, such as high river flows and coastal storm surge events.

Depending on the flood mechanisms being considered, and the nature of the statistical relationship between those processes, there may be several advantages to considering compound flooding in a regional flood modelling context. However, to ensure the feasibility of considering compound flooding, simplifications of the statistical correlation between processes may be needed, such as assuming colinear statistical dependence or statistical independence.

2.7 Climate and Land Use Change

Climate change refers to the long-term alteration of weather patterns (temperature, precipitation, atmospheric conditions) at a global scale. The impacts of climate change are numerous, often interconnected and potentially affect flood mechanisms at all scales. Based on this observation, the incorporation of climate change considerations in the development of regional flood models and in the definition of simulated scenarios can provide estimates of project flood impacts at a short-, medium-, or long-term. Similarly, land use changes, such as increased urbanization, alterations to wetlands, and deforestation due to wildfires, can have significant impacts on flood characteristics, particularly when considering the regional-scale impacts of those changes.

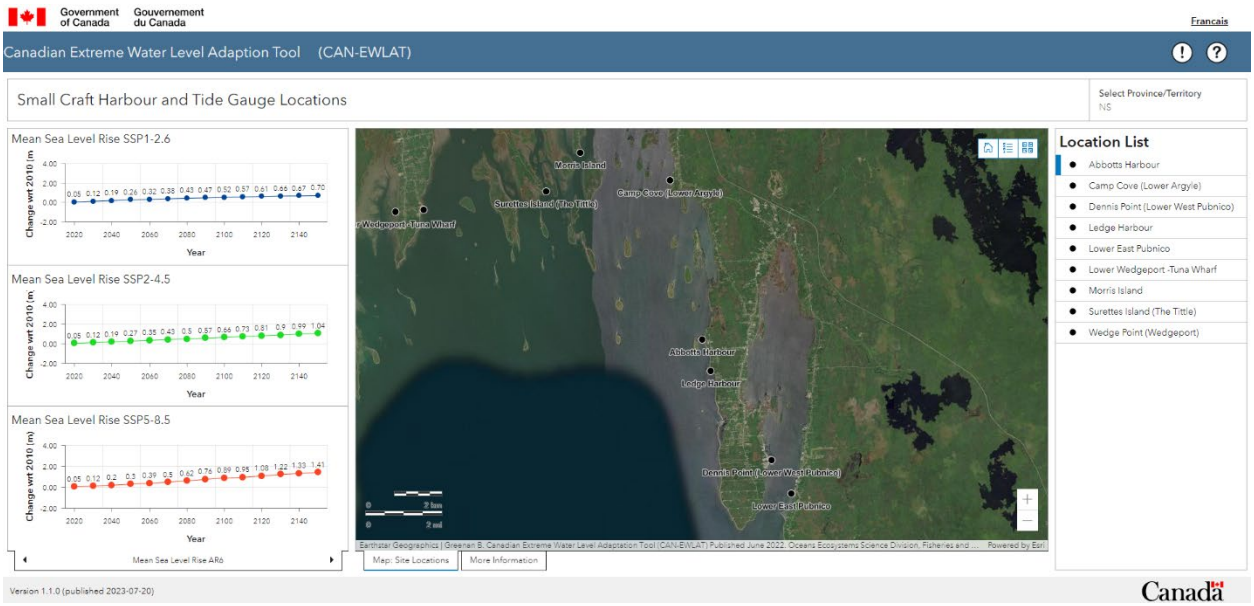
The Intergovernmental Panel on Climate Change (IPCC), established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO), serves as the leading international body for assessing the scientific basis of climate change and its impacts. The IPCC produces comprehensive Assessment Reports (AR) which summarize the latest climate science, impacts, adaptation measures and mitigation options. As part of the 6th Assessment Report (AR6), IPCC established Shared Socioeconomic Pathways (SSPs) which are scenarios used to characterize future development pathways based on possible evolutions of population, energy use, technology, etc. as well as ambitions and actions taken to mitigate climate change at a global scale. The SSP scenarios provide a well-defined and recognized framework for the assessment of future climate and capture the inherent uncertainty of climate change.

Over the years, several climate modelling institutions have developed and improved climate models to simulate climatic processes at global and regional scales and for various scenarios, including the Canadian Centre for Climate Services, Ouranos, the Pacific Climate Impacts Consortium, and ClimateWest. These models are based on a wide range of modelling software, parametrizations, computational resolutions and sometimes focus on the description of specific regions and climatic processes. The simulated projections of climate change can differ from one model to another. To account for this variability, flood modelling frameworks based on ensemble of simulations for a range of scenarios and projections and using various underpinning climate models, allow for the computation of statistical results derived from the simulated ensemble and the quantification of the uncertainty and variability of potential future floods.

The Coordinated Ocean Wave Climate Project (COWCLIP) is an international and collaborative initiative focusing on studying and understanding ocean wave climate variability and the potential evolution due to climate change. One of the objectives of the initiative is to provide ensembles of wave climate projections for subsequent use by the community. Such collaborative efforts support multi-model ensemble approaches to assess of impacts of waves on coastal flooding under climate change scenarios.

Sea level rise estimates are generally well described and understood throughout Canada. Up to date projections which account for local land subsidence are available for the latest IPCC projections throughout all of Canada using the Canadian Extreme Water Level Adaptation Tool (DFO, 2023), as shown on Figure 2. Secondary impacts from climate change such as a loss of sea ice or changes to storm intensity and frequency, are generally less understood and require more careful consideration. Sensitivity analysis and testing using regional modeling tools, supplemented by research and literature can provide lines of evidence for general guidance on incorporating such phenomena into regional mapping efforts. In lake environments, future lake level projections can also be considered from available research, as applicable, to inform future flood hazards. For example, it has been recently projected that the Great Lakes will see a rise in static water levels, relative to present-day baseline, due to a projected increase in precipitation in the Great Lakes watersheds. Additionally, in a changing climate, the loss or reduction of shore-fast sea ice is likely to increase coastal flood hazards, due to more frequent exposure of shorelines to winter storm events which can erode and exposure shorelines to greater storm surges and wave energy.

FIGURE 2: VISUALIZATION OF THE PROJECTED SEA LEVEL RISE IN THE CANADIAN EXTREME WATER LEVEL ADAPTATION TOOL



The integration of climate change impacts into fluvial flood hazard studies has historically been approached considered using qualitative or quantitative approaches. Qualitative approaches generally consist of reviewing anticipated climate change impacts and selecting an appropriate freeboard to add to return period flood events. Quantitative approaches leverage integrating projected climate change impacts into flood hazard extents using hydrologic and / or hydraulic models, such as the development of design storm hyetographs which consider climate change impacts and simulating those hyetographs in a hydrologic model. The resulting flow hydrographs can then be simulated in a hydraulic model. More recent guidance from NRCan provides further guidance on quantitative accounting for climate change impacts in flood hazard modelling, describing a strategy to leverage statistically downscaled global climate models with regional climate models and historical datasets, and ensuring the plausibility of the climate change projections. Recommendations are also provided for ensemble analyses of potential climate change impacts to understand the uncertainty associated with the range of projections.

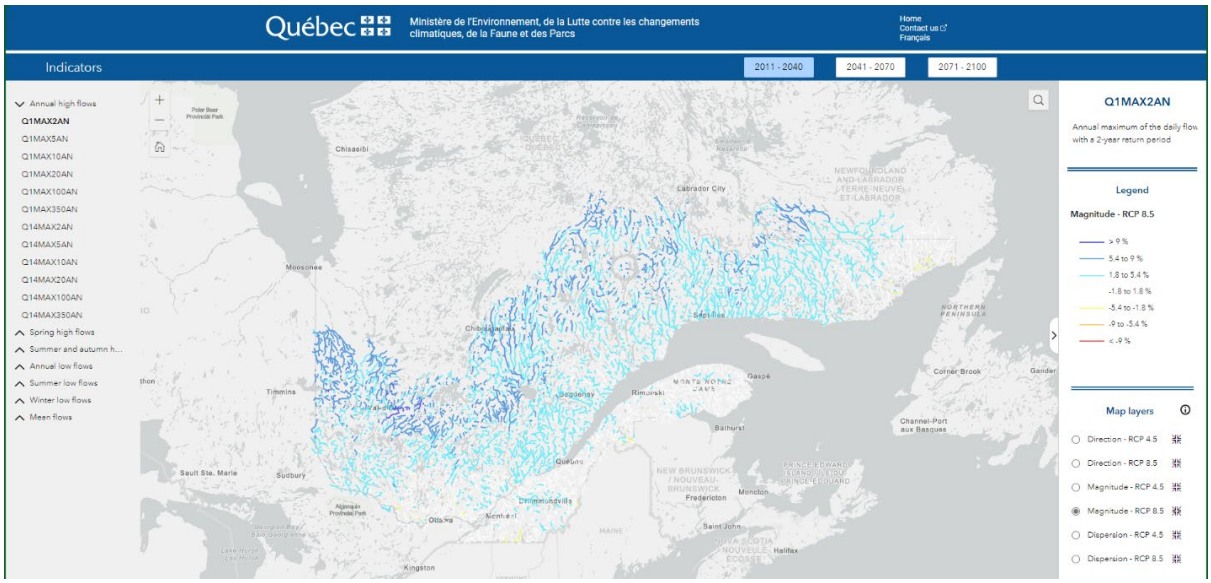
In 2024, the latest update on federal guidance from ECCC and NRCan regarding the integration of climate change within the FHIMP recommends to sequentially:

- Identify the main causes for flooding in the studied watershed.
- Assess how climate change might impact the flood mechanisms identified.
- Establish a conceptual model which addresses climate change effects.
- Proceed with the analysis.

The Hydroclimatic Atlas of Southern Québec (MELCCFP, 2022), as shown on Figure 3, provides access to water regimes in rivers in southern Québec for present-day and future climate and serves as a strong example of regional initiatives which support the characterization and dissemination of regional climate

change data and demonstrative impacts. This publicly available portal supports the implementation of water management practices that are resilient in a changing climate.

FIGURE 3: HYDROCLIMATIC ATLAS OF SOUTHERN QUÉBEC



Climate change and land use change are anticipated to have significant impacts on pluvial flood hazards, and as such it is critical to ensure that climate change and land use change impacts in the evaluation of pluvial flood hazards. Pluvial flood modelling is typically completed in the planning and design of stormwater management infrastructure, and as such, guidance documents on climate change are typically provided on a jurisdictional basis, with a focus on how climate change should be considered in the planning and design of stormwater management infrastructure. However, given that regional-scale pluvial flood hazard modelling and mapping in Canada is relatively limited, standardized guidance for integrating climate and land use change impacts into those regional-scale models is similarly limited. Accordingly, further research into evaluating climate change impacts in regional-scale fluvial flood hazard models should be pursued with the intent of developing standardized guidance for inclusion in Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation (NRCan, 2023). In general, and until clearer guidance is available regarding large-scale fluvial flood hazards, the general guidance provided for fluvial flood hazard modelling and mapping is an appropriate approach to integrating climate change impacts into pluvial flood hazard modelling and mapping.

3.0 OVERVIEW OF JURISDICTIONAL PERSPECTIVES

To assess current progress on regional flood hazard modelling and mapping in Canada, KGS and DHI met with several provincial, territorial and federal government agencies responsible for flood hazard mapping programs or engaged on regional scale modelling. It was not possible to meet with every jurisdiction in Canada due to logistical constraints. However, efforts were made to meet with a representative subset of provincial and territorial agencies. Table 2 provides an overview of current progress on regional flood hazard modelling and mapping across Canada.

TABLE 2: STATE OF PLAY OF REGIONAL FLOOD HAZARD MODELLING AND MAPPING

	Jurisdiction/Agency	Ongoing Regional Modelling/Mapping	Description
Provinces / Territories	**British Columbia**	Yes	BC Hydro / Fortis BC, and the Government of British Columbia are currently developing the methodology for regional scale flood hazard modelling and starting work on a coarse level model covering the province. Tier 1 and Tier 2 (i.e. regional scale flood hazard modelling) studies have been completed for some watersheds in the province.
	Alberta	Limited	Large-scale hydrologic modelling has been completed using the Modélisation Environmentale Communautaire - Surface and Hydrology (MESH) river model for Athabasca, Peace and Slave Rivers. No regional flood hazard methodology has been developed.
	Yukon	Limited	No regional scale flood hazard modelling has been completed. The Government of Yukon has worked with the University of Saskatchewan to develop a MESH hydrologic model that covers the Yukon River basin, in addition to older models of the Liard River basin (Yukon portion).
	Quebec	Yes	Québec has developed and implemented a regional scale flood hazard modelling methodology across the southern portion of the province (i.e. Info-Crue program, as described further in Section 4.2).
	Newfoundland and Labrador	Yes	Newfoundland and Labrador has completed regional modelling of storm surge and waves along sections of the Newfoundland and Labrador Coast for current climate and climate change conditions. Regional scale approaches for fluvial or pluvial flood hazard modelling are generally not applicable for Newfoundland and Labrador due to the distribution of small coastal communities along the coastline. In addition, NL is developing a coastal flood simulation tool for areas where LiDAR/HRDEM data is available, using a simplified bathtub approach to estimate coastal flooding.

	Jurisdiction/Agency	Ongoing Regional Modelling/Mapping	Description
	Nova Scotia	In Progress	Currently developing a methodology and set of guidance documents for regional flood hazard modelling in Nova Scotia. Aiming to develop a test case of this methodology for Cape Breton, then implement province wide.
	New Brunswick	Yes	Developed and applied a methodology for inland flood hazard modelling province-wide, excluding coastal watersheds and St. John River. Completed estimates of the 1, 2, 5, 10, 20, 25, 50, and 100-year water levels along the New Brunswick coastline. Sea-level rise estimates and associated extreme total sea levels have been prepared for future milestones of 2030, 2050 and 2100 for New Brunswick coastal sections. Completion of a Regional Wave Run-up Study by the National Research Council for the Province of New Brunswick providing regional estimates of extreme wave runup heights based on nearshore extreme wave conditions and shore types.
Federal Agencies	**Environment and Climate Change Canada (ECCC)**	Yes	The Environmental Forecasting Research division is currently conducting large-scale hydrologic model simulations using the Global Environmental Multiscale Hydrological Modeling Platform (GEM Hydro) hydrologic model. The project outputs include a 40-year record of streamflow reanalysis data covering approximately half of Canada's watersheds at an hourly time step.The Meteorological Research Division (MRD) has developed a light 3D baroclinic (9 vertical levels, 2-9 km resolution) Global Deterministic storm Surge Prediction System (GDSPS) to provide water level forecasts for all the Canadian coasts. The model dynamically includes important contributions from storm surges, tides, effects of density variation and sea ice, and their interactions. A 65-year global hindcast of hourly total sea level has recently been produced based on the GDSPS. MRD has also developed a 2D barotropic Regional Ensemble storm Surge Prediction System (RESPS) for the east coast, and it will be later transitioned into a light 3D Global Ensemble storm Surge Prediction System (GESPS) to provide guidance for all the coasts..

	Jurisdiction/Agency	Ongoing Regional Modelling/Mapping	Description
	Public Safety Canada	Global	Public Safety Canada has procured several Canada-wide 30 m by 30 m resolution flood hazard models. Public Safety Canada is currently working towards developing a Canada-wide model.
	National Research Council	Yes	Developed and applied several regional coastal models for different regions of Canada in order to provide input to higher resolution models. Mix of regional and local riverine modelling.
	Natural Resources Canada (NRCan)	Yes	Canada Centre for Mapping and Earth Observation (CCMEO) supports ongoing flood mapping work and regional modelling efforts across Canada by implementing over 200 projects with provinces and territories, as well as making available core data required for regional flood modelling (including a new medium resolution digital terrain model). Additionally, the Geological Survey of Canada has worked with Aquanty Inc. on the Canada1Water project to assess the impacts of climate change on Canada's water resources. A large-scale hydrologic and groundwater model was developed in HydroGeoSphere nationwide, including Canada's transboundary watersheds.

In general, jurisdictions across Canada are engaged in varying levels of regional flood hazard modelling and mapping. Several provincial / territorial jurisdictions (i.e., British Columbia and Nova Scotia) were in the process of developing a regional flood hazard modelling methodology at the time of these interviews. Regional flood hazard modelling projects had been implemented across Canada, including large-scale hydrologic modelling in the Yukon and Alberta, regional scale riverine flood hazard modelling in British Columbia, Quebec, and New Brunswick, regional scale pluvial flood hazard modelling in Prince Edward Island, and regional coastal modelling in Newfoundland and Labrador and New Brunswick. Quebec, New Brunswick, and Prince Edward Island have advanced flood hazard modelling to ensure near full coverage of the populated areas within each jurisdiction.

Federal agencies are also developing and implementing regional and global scale models. These projects include large-scale hydrologic modelling for streamflow reanalysis over approximately half of Canada's land area (ECCC), regional coastal modelling, and fully coupled surface and groundwater modelling for all watersheds in Canada (i.e. Canada1Water project) and water level forecasting for all Canadian coasts using storm surge prediction systems (MRD).

In the United States, federal agencies are applying regional hydraulic modelling to define riverine flood hazards as part of the Base Level Engineering (BLE) program as described further in Section 4.6. BLE was initially piloted in 2015, improving on previous large scale floodplain modelling assessments (FEMA, 2022). The Federal Emergency Management Agency FEMA has developed a methodology for BLE which is currently implemented to develop a baseline understanding of flood risk across the United States. BLE approaches include 1D, 2D or coupled 1D/2D large-scale hydraulic models developed in the Hydrologic Engineering Center's River Analysis System (HEC-RAS) based on LiDAR data and is intended as a largely automated flood hazard delineation process that can be flexibly updated and refined as newer or better data becomes available. FEMA aims to tailor the scale of modelling depending on the level of development and risk, with less detail in rural areas and federal lands that can then be fed into smaller, higher resolution model domains with a higher level of detail where the results may be used for planning purposes. FEMA also has a well-defined methodology for regional hydrodynamic and wave modelling which has been implemented for participating communities across the populated coastline of the continental United States.

There were generally favourable opinions on the suitability and usefulness of regional flood hazard modelling and mapping, although some concerns were expressed regarding the overall utility of the resulting hazard mapping. Some jurisdictions expressed concern about the coarser scale and noted that there was a need for clarity of messaging to the public regarding the resulting products and how they compare against detailed engineering level mapping products. However, those jurisdictions did note that the potential use cases of high-level screening, emergency response or public awareness were considered valid.

Feedback was expressed by jurisdictional representatives that the guidelines should avoid being overly prescriptive, and instead that a more flexible approach be taken to the guidelines such that jurisdictional preferences or standards could be respected. Recommendations were also provided that the guidance documents should consider subdividing the regional level into further tiers that relate the methodological approach, data sources, and data quality to the anticipated level of accuracy and appropriate use cases. Similarly, it was recommended that regional flood hazard mapping products be compared to detailed flood hazard mapping products to understand the potential range of accuracy that could be expected from the regional approach. It was also highlighted that clarity is required regarding the definition of 'regional scale,'

as there are significant differences in scale between global flood hazard products and detailed flood hazard maps.

4.0 REGIONAL MODELLING PROJECT HIGHLIGHTS

4.1 Overview

As noted in Section 3.0, a number of regional flood hazard modelling and mapping projects are ongoing in Canada and the United States of America. Projects from different regions of North America are described in this section, highlighting the different approaches that are being adopted to assess a range of flood mechanisms. Key aspects of the projects, such as the modelling methods and software that were used, anticipated use cases, and key lessons that were learned through the execution of those projects, are included in the project highlights.

4.2 Info-Crue

Info-Crue is a flood hazard mapping and forecasting system whose development was led by the Government of Québec's Ministère de l'Environnement, de la Lutte contre les Changements Climatiques, de la Faune et des Parcs (MELCCFP), and supported by a number of agencies, including Ouranos, the Government of Canada, hydroelectric providers within Québec, academia, local levels of government, and residents. The development of Info-Crue was motivated by large scale flooding that occurred during 2017 and 2019, as well as the ongoing significant annual costs associated with flooding, and the apparent need to complete flood hazard mapping at a large scale to understand flood hazards throughout the province.

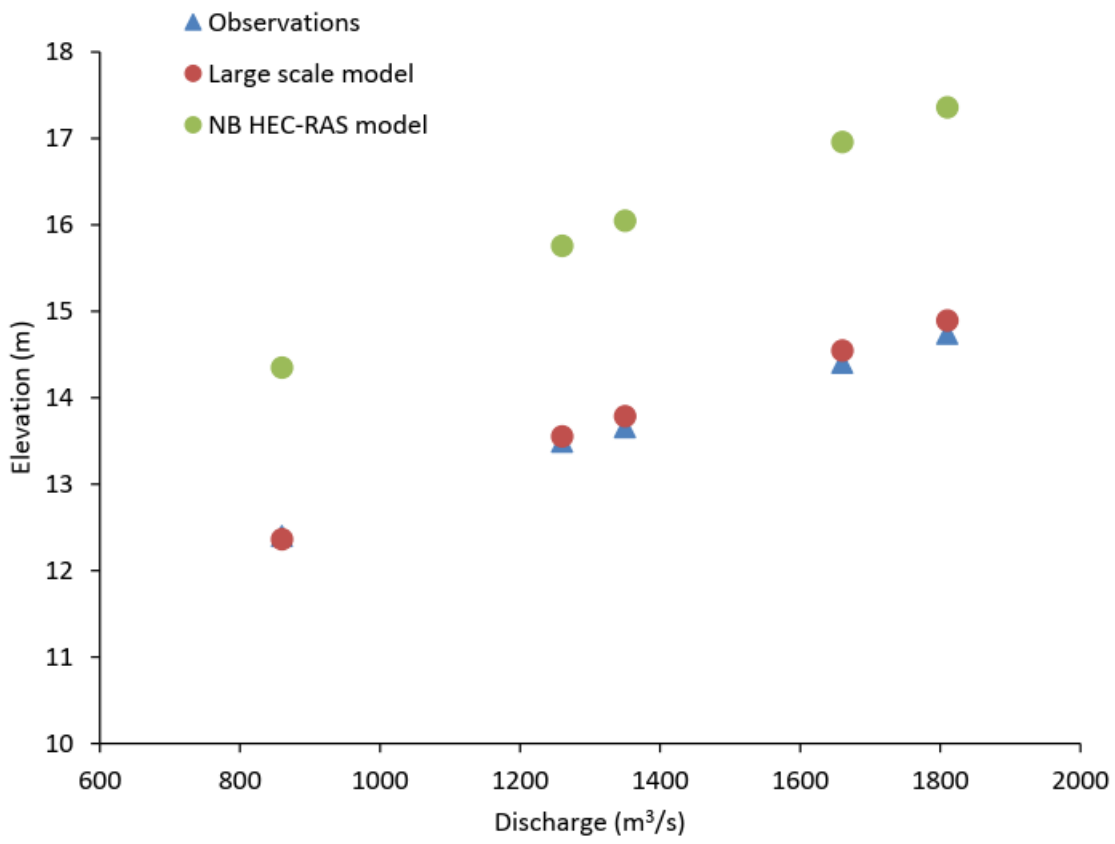
Initially, Info-Crue was envisioned as a flood forecasting system and a database of flood maps to support municipalities in evaluating flood risks within their territories. As the regulatory framework for flood hazard mapping in Québec has evolved, with responsibilities shifting from municipal to provincial authorities, the scope of the project was broadened to include the simulation of return period floods to define regulatory flood hazard mapping products across a wider portion of Québec's territory. The Info-Crue model represents 50 watersheds in Quebec, with approximately 8,000 km of lineal river length represented in the models. The watersheds considered in Info-Crue are shown on Figure 4.

FIGURE 4: WATERSHEDS CONSIDERED IN INFO-CRUE



The large regional domain of the Info-Crue model required substantial input data, as well as innovative modelling techniques to practically implement the model. The primary basis for the models is LiDAR data that has been collected throughout the full study area. To estimate river bathymetry, a novel methodology developed by Concordia University was implemented throughout the model domain (Bessar et al., 2021, Choné et al., 2021). The river bathymetry estimation process leverages data from the provincial HYDROTEL hydrological model to estimate flows at time of LiDAR capture, in combination with the calculated width of the river, the apparent water level on the river, and an inverse 1D hydraulic modelling approach to estimate the river depth. Hydraulic equations cannot be resolved in areas with zero slope, which is a limitation of this methodology. Further testing of this method by Concordia University on the Southwest Miramichi watershed in New Brunswick found that it resulted in significant improvements to the accuracy of the hydraulic models, as shown on Figure 5. Given the model scale, it was not feasible to integrate hydraulic structures in the model, although the bathymetric estimation did provide some estimation of conveyance. The impact of structures is approximated in some cases, such as width reduction at bridges, while large storage capacity dams are either integrated directly into the model when data are available or used as downstream boundary conditions.

FIGURE 5: COMPARISON OF MODELS WITH AND WITHOUT BATHYMETRIC CORRECTIONS (CHONÉ ET AL., 2023)



Info-Crue was initially developed using the LISFLOOD model. However, during development, the models were converted to use HEC-RAS 2D due to its broader functionality, established use within the engineering community, and long-term support provided by the USACE. Inflows to the model are defined by a HYDROTEL model that was developed, calibrated and validated by the MELCCFP throughout the province. The HYDROTEL model includes sub-watersheds with a minimum drainage area of 100 km^2. Smaller watersheds are incorporated using a modified rational method to estimate flow values (Mailhot, Bolduc, & Talbot, 2023). The resolution of the HEC-RAS models varies according to the topography and level of development throughout the model domain, but generally consist of resolutions ranging from 8 to 32 m in the floodplains, with 4 to 5 cells representing watercourses. Watercourses that are less than 4 m wide are not represented in the mesh.

The overall high level of resolution, and significant special extents required that an innovative approach be developed to ensure that the simulation of flood events within Info-Crue would be technically feasible. To do so, the model domains were subdivided into smaller domains, and customized coding was developed to simulate the models in series. Synthetic hydrographs, based on drainage area, specific discharge, and peak factors, are injected into downstream models. The resulting stage data from unsteady flow simulations in these downstream domains are used to generate rating curves at their upstream boundaries, which are then applied as boundary conditions in the upstream models. In rare cases, such as backwater zones, tidal areas,

or complex confluences, a stage hydrograph is used instead. Where available, calibrated rating curves from gauging stations, dams, or validated models are incorporated to reduce bias throughout the model chain.

A number of key lessons were learned through the execution of the Info-Crue project, including:

- The need for extensive LiDAR coverage is key to ensure the accurate representation of floodplains, as this data can also be used to estimate river bathymetry.
- A number of tasks, such as the estimation of river bathymetry or digitizing stream banks, are well suited to automation, and would significantly reduce the workload associated with the development of the model.
- A substantial amount of customized software and coding development work was required in the execution of the project, and as such coding resources served a key role in the development and execution of the model, in particular to enable the simulation of models in series to minimize computational demands.

4.3 Regional Coastal Flood Mapping Project for the Capital Region District

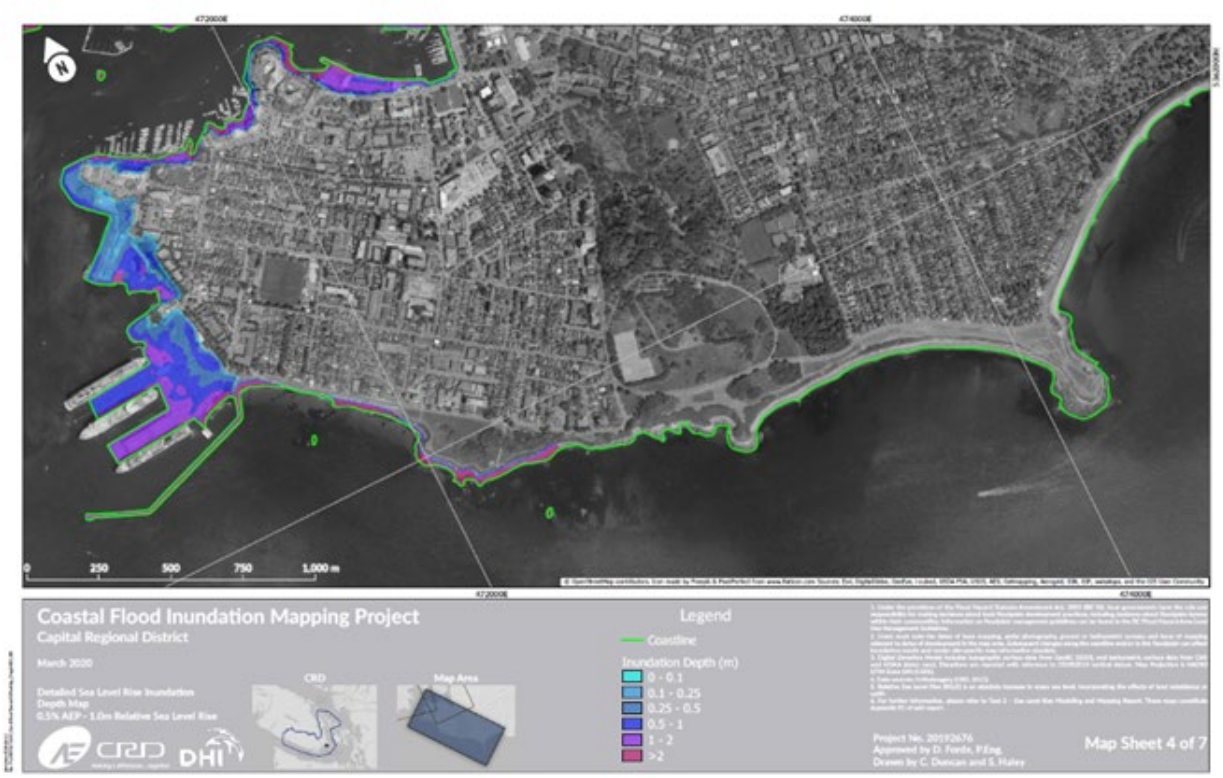
The Regional Coastal Flood Inundation Mapping Project aims at better understanding regional impacts from coastal storm flooding due to sea level rise and tsunamis for the Capital Region District located at the southern end of Vancouver Island and the southern Gulf Islands in British Columbia. The capital region has a long and complex coastline, approximately 1,300 km in length, with several low-lying areas exposed to coastal flood hazard now, and into the future with sea level rise.

The project was completed with support from the federal and provincial National Disaster Mitigation Program. The project required innovative modeling methods and various tiers of modelling on a large geographical scale to provide coastal flood hazard information to:

- Help planners and emergency managers prepare the region for coastal storm and tsunami events that may impact southern Vancouver Island and the Southern Gulf Islands.
- Offer guidance to regional stakeholders to inform coastal flood policy, planning and communication efforts.
- Better understand the infrastructure, ecosystems and cultural sites that may be at risk due to future sea level rise.
- Identify risks to residents and infrastructure (e.g., harbours, marinas, docks) within the capital region as a result of tsunami waves and currents, as shown on Figure 6.

A project of this magnitude required a very large collection of input data, where most of the data is publicly available. Data included, but was not limited to, Canadian Hydrographic Service (CHS) long-term water level gauging records, bathymetric surveys, buoy data and meteorological records, numerous Environment Canada and Climate Change, NOAA, and United States Geological Survey (USGS) meteorological station data to characterize regional winds, global tidal models, bathymetric survey data from the CHS Non-navigational (NONNA), NOAA, U.S. Navy, and USGS, B.C. shoreline LiDAR data, local topographic surveys, records of flooding, and various lines of evidence of flood impacts.

FIGURE 6: EXAMPLE CAPITAL REGION FLOOD HAZARD MAP



The modelling approach implemented for this project consisted of a refined form of the probabilistic method from the Provincial Guidelines to derive flood construction levels (FCL) based on assessment of total water levels for four sea level rise scenarios (i.e. 0 m, 0.5 m, 1.0 m, and 2.0 m), and five annual exceedance probabilities (AEP). The approach accounted for the joint probability of occurrence of all the different processes contributing to coastal flooding, such as sea level rise, high tide, local and regional surge, and wave effects (i.e. set-up and run-up).

The hydraulic modelling was completed using the MIKE 21/3 modelling suite for Hydrodynamic and spectral wave models, and the FUNWAVE TVD software for Tsunami modelling. The scenarios considered in the study included:

- Mapping the flood construction levels for the 1.0 m and 2.0 m sea level rise scenarios.
- Mapping still water level for a 0.5% AEP for the 1.0 m and 2.0 m sea level rise scenarios.
- Detailed modelling and subsequent mapping of flood extent and depth for five study sites.
- Total water levels for all relative sea level rise scenarios and the five different AEPs.
- Maximum water levels in each community for 11 tsunami events.

4.4 Pluvial Flood Modelling in Prince Edward Island

The University of Prince Edward Island (UPEI) completed an experimental project to develop an island-wide pluvial flood hazard model to develop pluvial flood hazard maps (PEI, 2024). Due to PEI's widely distributed

population, regional flood hazard modelling can fill a gap in flood hazard information for less populated areas.

A number of different approaches were evaluated to generate pluvial flood hazard information, with UPEI ultimately landing on implementing a rain-on-grid approach in a 2D HEC-RAS model. The basis for the HEC-RAS model was LiDAR data that was captured throughout the full extent of the province. Modifications were made to the DEM to represent the hydrologic network throughout the province. Adjustments were also made to the DEM to approximate the hydraulic connectivity associated with culverts, although all culverts smaller than 1.2 m in diameter were assumed to be 1.2 m in diameter. One key limitation of the model is that channel bathymetry was not estimated or included in the DEM, which would under-represent channel conveyance. However, since the focus of the modelling was pluvial flooding, this was less of a concern than for fluvial flood hazard modelling.

The HEC-RAS model resolution consisted of 100 m grid spacing, with 20 m mesh refinements along rivers and road networks. More detailed modelling was undertaken in the main cities and communities on PEI, with 10 m grid spacing and 2 m refinement along rivers and road networks. The grid size was developed based on testing and optimization considering the computational efficiency, grid cells, and model stability. Additional data was integrated into the 2D HEC-RAS model to estimate soil infiltration capacity, including provincial soils data and land cover data.

Rainfall data from ECCC IDF stations were used to define current climate design storm events for the 10, 25, 50, and 100-year return periods. IDF curves including climate change impacts were similarly used to define storm events under climate change conditions considering the SSP 8.5 high emissions scenario during the 2071 – 2100 timeline. These design storms were integrated into the HEC-RAS model to represent the design rainfall conditions, with the resulting flood hazards integrated into an online platform, as shown on Figure 7.

FIGURE 7: REGIONAL PLUVIAL FLOOD HAZARD MAPPING



To estimate the mitigating impacts of stormwater infrastructure in urban areas, it was assumed that the stormwater systems could safely convey a 2-year rainfall event, and as such the design storms in urban areas were reduced by the 2-year rainfall event to account for the stormwater infrastructure. Coastal boundary conditions were integrated into the HEC-RAS model, and assumed the 1.6 year return period flood elevation based on the 2020 High-Flood Hazard Scenario for current climate conditions, and the 2100 Moderate-Low Flood Hazard scenario for future climate conditions. UPEI acknowledged that extreme flood events can include both high seas and heavy rainfall, although this has not yet been considered in the modelling work.

One of the key challenges of the study related to limited available hydrometric information for model calibration and validation. To address the limited available hydrometric data, model calibration and validation has been supplemented with delineations of historical floods, field survey work, and the inclusion of local knowledge of historical floods.

4.5 Halifax Regional Municipality

Climate Change is anticipated to increase in the frequency and intensity of extreme weather events across Canada, including in the Halifax Regional Municipality's (HRM). The HRM climate action plan (i.e. HalifACT: Acting on Climate Together) recognizes flood hazard mapping as an essential tool to support municipal staff in decision making related to current and future planning, critical infrastructure prioritization, and emergency planning and operations.

The study region is significant, covering nearly 5,500 km², and is therefore considered a regional assessment. In this context, CBCL Limited (CBCL) produced bespoke pluvial-fluvial and coastal spatial flood hazard maps for the entire HRM under multiple climate scenarios, recurrence intervals, and time frame combinations, as presented in Table 3. For climate change projections (2050 and 2100), RCP 8.5 (median) climate scenario was selected and Fifth Coupled Model Intercomparison Project (CMIP5) downscaled models available on ClimateData.ca were used to support the study, for the estimation of projected rainfall and sea level rise.

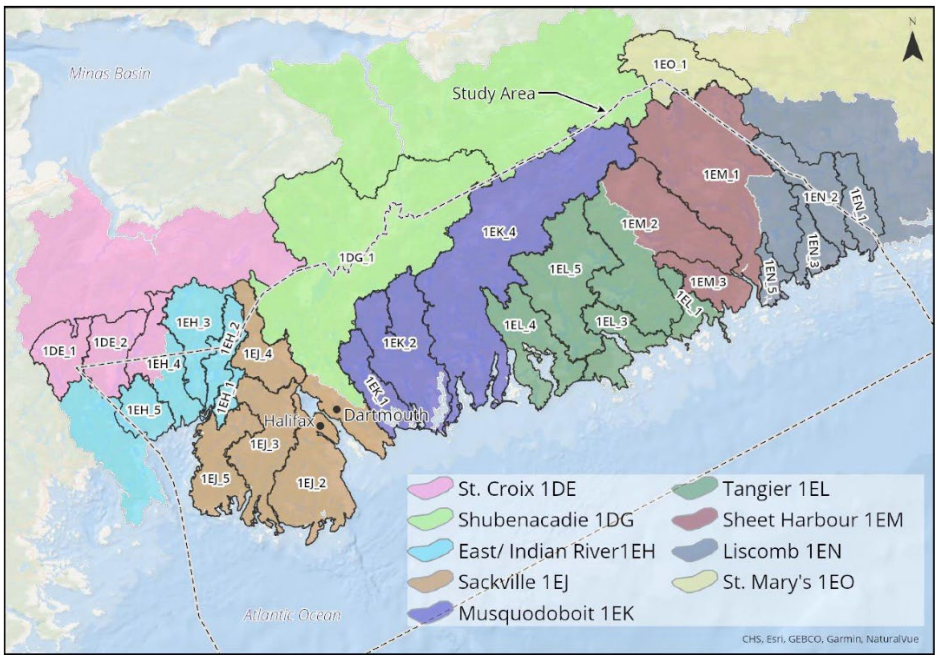
TABLE 3: FLOOD EVENT PROBABILITIES INCLUDED IN THE STUDY (CBCL, 2023)

Return Period	Time Horizon	Intended Use
2	2022, 2050, 2100	Emergency Management, Infrastructure
5	2022, 2050, 2100	Emergency Management
10	2022, 2050, 2100	Emergency Management
20	2022, 2050, 2100	Emergency Management and Land Use Planning
50	2022, 2050, 2100	Emergency Management
100	2022, 2050, 2100	Emergency Management and Land Use Planning

Return Period	Time Horizon	Intended Use
200	2022, 2050, 2100	Land Use Planning
500	2100	Infrastructure Prioritization
1000	2100	Infrastructure Prioritization

For the Pluvial-Fluvial modelling component of the study, the inland portion of the study was divided into 9 study regions based on the provincial Primary Watershed designations and further split into 27 sub-watersheds, as shown on Figure 8. An integrated hydrological-hydraulic model was prepared using the PCSWMM software. The project scope excluded any new survey work, relying solely on existing data and heavily utilizing automated methods for hydrologic and hydraulic modeling.

FIGURE 8: SUB-WATERSHEDS FOR THE INLAND (PLUVIAL, FLUVIAL) STUDY REGIONS (CBCL, 2023)



The regional scale of the study area and the extensive length of the watercourse to be mapped was challenging to model due to the complexity of urban and municipal infrastructure throughout the watershed, which traditionally necessitates a high level of detail and data to resolve. In keeping with the objectives of a regional assessment, and to minimize the need for detailed manual adjustments across the study area, the modeling detail was increased to a 50-meter cross-section spacing, allowing the topography to be better represented in the model.

The study area contains numerous hydraulic structures, including dams, weirs, bridges, and culverts. Efforts were made to produce estimates that accurately represent the capacity of these drainage structures. These

estimates aim to provide a general understanding of how the structures affect upstream flooding and downstream flows and are resolved at a level of detail appropriate for a regional scale assessment. The results are expected to be sufficiently accurate for larger bridge structures, where the LiDAR geometry generally provides a good representation of the hydraulic opening. For smaller structures, there is a greater degree of uncertainty. However, this uncertainty is related to smaller flows and consequently has smaller associated impacts.

Flood mechanisms such as ice or debris jamming, rain with snowmelt, and specific seasonal conditions, which may be pertinent to infrastructure design and detailed site-specific assessments, were not included in the scope of this study. Additionally, flood mechanisms relating to dam operations and hydraulic control structures in the watersheds have not been explicitly incorporated into the models and analysis. Where present, dam and control structures were modelled as passive and without active operation such as storage or release of flows. However, the calibration results demonstrated a good correlation between measured flow data from ECCC stations and modeled flows at seven sites within the HRM. The climate change assessment and scenario definition enabled the evaluation of risks linked to the uncertainties of a changing climate.

To support the delineation of regional coastal flood hazards, a coupled MIKE 21 HD/SW model was setup to simulate the local storm surge expected for the 1 in 2-, 5-, 10-, 20-, 50-, 100-, 200-, 500-, and 1000-year return period storm events in HRM's coastal zone. The simulated wind and wave conditions were determined based on extreme value analysis of offshore hindcast data from DFO MSC50. The offshore water level input to the model was initially derived from offshore storm surge estimates and HHWLT levels and then calibrated until the modelled water levels matched extreme values computed from measurements at Halifax (BIO) long-term tide gauge.

The modelled storm surge was then combined with sea level rise projections (2020, 2050, or 2100, RCP8.5 median) by applying a uniform SLR value throughout the domain. The output of the regional coastal modelling is a spatially varying extreme water level along HRM's coastal zone, with a spatial resolution down to 100 m. Local-scale and site-specific factors such as wave run-up, overtopping, and coastal erosion were not within the study's scope. Furthermore, tsunami risk was also excluded from consideration in the study.

Flood lines for coastlines and rivers were prepared separately based on the Pluvial-Fluvial and Coastal modelling results to depict the conditions of the Annual Exceedance Probability (AEP) scenario for each of the riverine and coastal flood mechanisms. Seen as the first step of a larger comprehensive initiative designed to provide HRM with the necessary tools to identify climate-driven flooding hazards, this set of maps is intended to support the initial identification of flood hazards, emergency responses, urban planning, and enhancing infrastructure resilience.

4.6 Base-Level Engineering

Base Level Engineering (BLE) is an approach implemented by the U.S. Federal Emergency Management Agency (FEMA) to develop a baseline understanding of flood risk across the United States. BLE refers to the level of detail and model requirements that underpin the resulting modelling and mapping products, specifically large-scale 2D hydraulic models developed based on LiDAR data. BLE flood hazard mapping builds on previous regional flood hazard modelling and mapping work completed by FEMA, specifically the First

Order Approximation (FOA) and Large Scale Automated Engineering (LSAE) datasets. BLE is intended as a largely automated flood hazard delineation process that can be flexibly updated and refined as newer or better data becomes available.

Flood hazard information is currently being developed for different regions across the United States to fill gaps of flood hazard information. The BLE program uses 1D, 2D or coupled 1D/2D hydraulic models in HEC-RAS to estimate flood hazard extents. FEMA aims to tailor the scale of modelling depending on the level of development and risk, with less detail in rural areas and federal lands that can then be fed into smaller, higher resolution model domains with a higher level of detail where the results may be used for planning purposes.

FEMA describes a number of classes of BLE modelling, considering key model considerations, and providing guidance on the most appropriate uses, regulatory applications, and potential cautions or limitations. Key aspects of the classification of BLE include:

- Cross sections (1D) or mesh refinement (2D) considerations;
- The representation of hydraulic structures;
- Manning's n value and land cover;
- Level of detail along flow paths.

The project has a mandate to assess fluvial, pluvial, and coastal flooding. FEMA is currently assessing the best approach to addressing pluvial flooding, with potential application of limited rain-on-grid domains in urban areas and fluvial considerations elsewhere in the model domain. Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) stochastic storm transposition is another potential means of assessing pluvial flooding.

One of the key challenges encountered by FEMA in the implementation of BLE flood hazard mapping related to the jurisdictional interpretation of the suitability of the delineated flood hazards for different use cases. FEMA found that certain jurisdictions were using the BLE data for use cases that required a much higher degree of precision than was available from the BLE dataset. This led FEMA to provide guidance on the appropriateness of the BLE datasets to different use cases depending on the classification of the BLE dataset.

4.7 Newfoundland & Labrador Atlas of Storm Surge and Wave climates

The Newfoundland & Labrador Atlas of Storm Surge and Wave Climates is being developed for the Government of Newfoundland & Labrador Water Resources Management Division (WRMD) and is intended to inform coastal floodplain mapping efforts throughout the province, and to provide a consistent basis for the modelling and interpretation of coastal processes and hazards related to flooding.

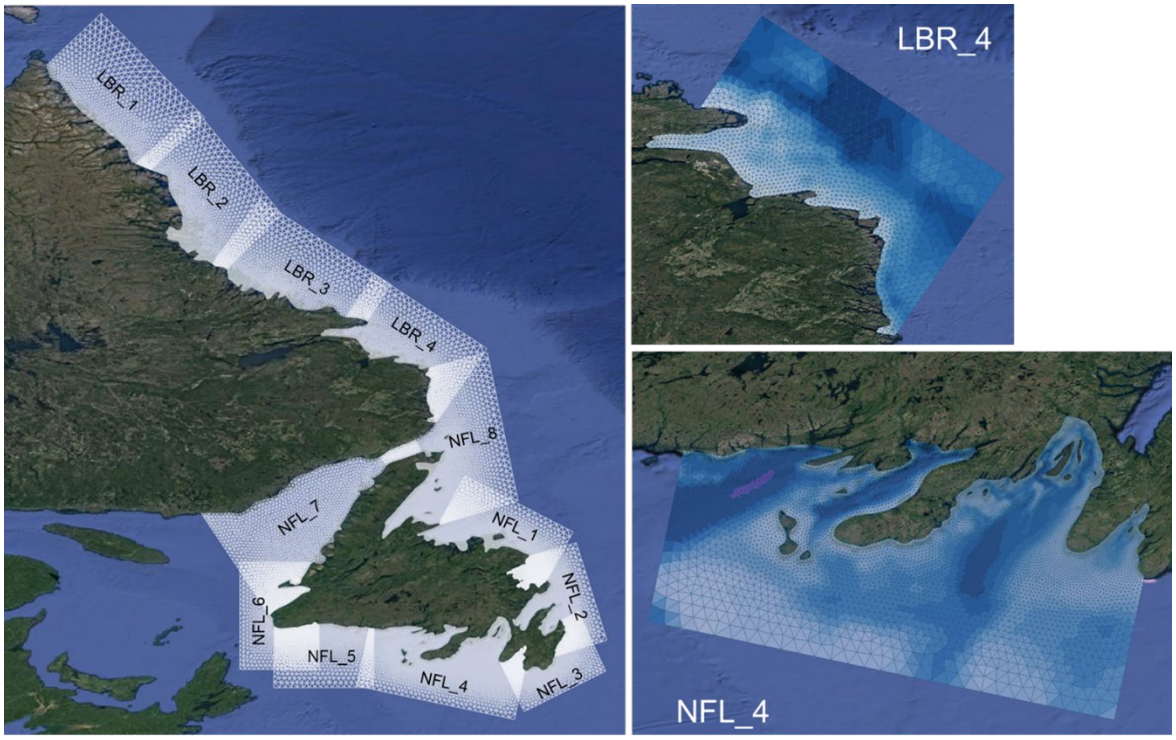
The digital dataset provides insight into the present and future patterns and characteristics of storm surges and waves along the province's coastlines. It consists of a vast array of information to support the assessment of coastal flooding hazards, including:

- Time series of Water Level Residuals, Wave parameters (Significant Wave Height, Peak Period, Mean Wave Direction) and Ice Concentration for 5,830 output points along the coast of the Province.
- Extreme Value Analysis for 78 points selected to be representative for areas of importance

- Maps of Water Level Residuals and Significant Wave Height 50th and 99th percentile and Average Annual Maximum values.

At the core of the Atlas lies a set of advanced numerical models developed specifically for this initiative which cover the entire province's coastline with spatial resolutions as fine as 1.5 km, as shown on Figure 9. These models were validated against measurements at various points around the province, where measurements are available, demonstrating their capacity to represent the storm surges and waves in the area and were applied to generate a 43 year hindcast and climate change projections.

FIGURE 9: ILLUSTRATION OF THE WAVE MODEL'S SUBDOMAINS COVERING THE PROVINCE'S COASTS



For a first evaluation of potential changes to the storm surge and wave climates due to climate change, two Global Climate Models (GCM) were used to force models and simulate Mid-century (2041-2070) and late century (2071-2100) conditions. The selected models are the EC-Earth3 and ACCESS-CM2 from the Coupled Model Intercomparison Project (Phase 6) (CMIP6) and the SSP5-8.5 scenario was retained as it represents a high-end emissions scenario that can be used to explore the potential impacts of a future where emissions continue to rise at a high rate.

Regional sea level changes from an ensemble of models from the Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report (AR6) and sea-ice concentration from the selected GCM were used to force the models. The outcome of the climate change modelling, covering the entire province, includes Mid-Century (2041-2070) and Late-Century (2071-2100) maps of projected changes in Storm Surge and Significant Wave Height statistics (50th and 99th percentile and Average Annual Maximum). The projected changes are relative

to the historical baseline (1985-2015), considering the SSP5-8.5 scenario for two Global Climate Models (EC-EARTH3 and ACCESS-CM2).

While both climate models consistently forecast an elevation in average wave conditions and surge levels along the Labrador coast due to reduced ice cover, findings from the simulations indicate less pronounced trends. The disparities between the simulations of the two GCMs and across the studied area underscore the necessity of a multi-model ensemble approach. Such an approach allows capturing the inherent variability in climate change scenarios. By incorporating an extended ensemble of models, a more nuanced and comprehensive perspective on projections and their impact on regional processes can be provided.

5.0 ENGAGEMENT WITH GOVERNMENT, ACADEMIA, AND INDUSTRY

5.1 Key Themes

5.1.1 DATA AVAILABILITY

Many engagement sessions highlighted that there are often inconsistencies between regional and national datasets, due to different underlying information and assumptions that were used to develop those datasets, as well as limited available information regarding flood defenses. This is further compounded by local corrections being applied inconsistently between datasets. In many cases, there may be advantages to leveraging regionally derived datasets rather than national datasets, as regionally derived datasets would likely include the incorporation of local information and knowledge. However, recent work, such as the Canada1Water project, have been working towards updating and harmonizing geospatial data such as the hydrologic network throughout Canada, which was identified as a key limitation in national hydrological datasets. Key input datasets for hydrologic, hydraulic, and coastal modelling at the regional scale are highlighted in Table 4.

TABLE 4: HYDROLOGIC, HYDRAULIC, AND COASTAL MODELLING INPUT DATASETS

Product	Description	Source
Digital Elevation Model and Bathymetry		
Canadian Digital Elevation Model	0.75 arc seconds x 0.75 arc seconds up to 0.75 arc seconds x 3.0 arc seconds	NRCan (2013)
High Resolution DEM	1 m to 2 m resolution based on high-resolution LiDAR, where available Full-coverage 2 m Digital Surface Model derived from ArcticDEM north of 60° latitude.	NRCan (2024a)
ArcticDEM	Digital Surface Model 2 m resolution Full coverage north of 60° latitude	Polar Geospatial Center (2023)

Product	Description	Source
	Reduced resolution available (10 m, 32 m, 100 m, 500 m, 1 km)	
FabDEM	1 arc second	Hawker et al. (2022)
Medium Resolution Digital Elevation Model (MRDEM)	30 m resolution	NRCan (2024b)*
Canadian Hydrographic Service Non-Navigational (NONNA) Bathymetric Data	10 m to 100 m	Canadian Hydrographic Service (2023)
Eastern Canada, 3" DEM	3 arc-second Bathymetric Digital Elevation Model	NOAA (2017)
Great Lakes Bathymetry	Collection of Great Lakes bathymetric data	CHS/NOAA (1996-1999)
Gridded Bathymetry Data	Global terrain model on a 15 arc-second interval grid	GEBCO (2023)
Province Specific LiDAR data	LiDAR data for New Brunswick, Nova Scotia, Alberta, Québec	Various GeoNB/GeoNOVA QC Forêt Ouverte
Land Cover		
2020 Land Cover of Canada	30 m resolution	Government of Canada (2020)
ESRI Land Cover	10 m resolution	ESRI (2023)
Province Specific Land Use Data (Utilisation du territoire – jeu de données)	Québec: 10 m resolution	MELCCFF (2023)
Atmospheric Conditions		
Australian National University Spline (ANUSPLIN) Interpolated Gridded Dataset	Gridded observational daily minimum and maximum temperature and precipitation data 300 arc second resolution	Hopkinson et al. (2011) and McKenney et al. (2011)
CaPa	10 km resolution gridded data 6-hour precipitation	ECCC (2019)

Product	Description	Source
Engineering Climate Datasets	IDF curves for approximately 600 locations.	ECCC (2024a)
Meteorological Data	Climate observations (temperature, precipitation, snow, wind) across Canada.	ECCC (2024b)
ERA5	Atmospheric reanalysis data 31 km grid	Hersbach et al. (2017)
North American Regional Reanalysis	Reanalysis temperature, wind, and soil moisture data 32 km grid	Mesinger et al. (2006)
HRDPS	High Resolution Deterministic Prediction System Atmospheric Forecast	ECCC (2022)
MSC50	Hindcast wind and wave models for the Canadian Coast	MSC/Oceanweather (2023)
CFSR/CFSv2 Global Hindcast	Hindcast ocean-atmospheric global model, inc. wind speeds and air pressure	NOAA (2011)
NRT Surface Winds	Remotely sensed surface wind derived from scatterometers and radiometers	CMEMS (2024)
ASOS/AWOS-METAR	Airport weather reports, including wind speeds and air pressure	FAA (2024)

Product	Description	Source
Hydrometric and Water levels		
DFO Tidal Gauges	Observed and predicted coastal water level data	DFO (2022)
WSC Gauges	Observed streamflow and water level data, hydrometric network drainage basin polygons	WSC (2024)
WebTide	Tidal Prediction Model	BIO (2023a)
L4 NRT Geopotential SSH	Altimeter satellite gridded Sea Level Anomalies	CMEMS (2023a)
Atlas hydroclimatique	Observed and predicted streamflow and water level data for rivers in southern Québec	MELCCFF (2022)
Waves		
MSC50	Hindcast wind and wave models for the Canadian Coast	MSC/Oceanweather (2023)
Moored buoys Measurements	Moored buoys measuring hourly weather and sea state	Various DFO/ILM/NDBC/NERACOOS /ECCC
NRT Wave Height	Remotely sensed significant wave height from altimeter	CMEMS (2023b)
Ocean Data collection	Sparse measurements of wave conditions (project-based)	CIOOS (2019)
PRIMED Wave Buoys	Sparse measurements of wave conditions (project-based)	University of Victoria (2023)

Product	Description	Source
SmartAtlantic Buoys	Sparse measurements of wave conditions (project-based)	CTec/COVE (2024)
Sea Ice		
Daily ice coverage	Ice charts describing latest ice conditions in regions of known marine activity.	CIS (2024)
L4 NRT Ice Coverage	Sea ice area fraction dataset based on passive microwave data	CMEMS (2023c)
Nimbus-7 SMMR Sea Ice Concentration	Grid cell size of 25 x 25 km	NSIDC (2022)
RADARSAT	Canadian remote sensing Earth observation satellite program (e.g., radar images).	CSA (2019)
Climate Change		
CAN-EWLAT	Science-based planning tool for future water level extremes	DFO (2023)
RSLR	Relative Sea-Level Change for the Canadian Coast.	James et Al. (2021)
CanDCS-U6	Newly downscaled Global Climate Models for all of Canada	PCIC (2018)
NA-CORDEX	Regional Climate Model ouputs covering the North American domain (various modelling centers; CMIP5 boundary conditions)	NSF NCAR (2013)
CanRCM4 Large Ensemble	Regional Climate Model with 50 runs (CMIP5 boundary conditions)	ECCC (2018)

Product	Description	Source
SDSM	Statistical DownScaling Model Software, for downscaling of daily surface weather variables.	Loughborough University (2015)
Other		
Sub-surface gliders	Missions collecting data on physical, biological, and chemical processes	CEOTR (2022)
L4 NRT Geostrophic Currents	Ekman and Geostrophic currents at the Surface and 15m	CMEMS (2023d)
Ocean Data Inventory	Inventory of moored current meters, thermographs, and tide gauges from the East Coast of Canada	BIO (2023b)

*Publication pending.

It was noted that LiDAR coverage varies across the country, and is often cited as a crucial data gap for regional modelling. The timeliness of LiDAR data and availability of repeat surveys was noted as a challenge, particularly in areas with highly mobile rivers that can shift following a flood, where geomorphological processes quickly result in significant discrepancies between LiDAR and the actual river geometry. Limited bathymetric data was also highlighted as another critical data gap.

The University of Concordia has developed a method to estimate channel geometry where bathymetric data is unavailable, as described in Section 4.2. Similarly, BGC Engineering developed an approach to reduce the design flows by the estimated flow at the time of LiDAR capture to account for the lack of bathymetry. However, it was noted that these methods rely on having LiDAR data available. Furthermore, it was noted that this process would be much more efficient if LiDAR swaths were collected along waterways, rather than in the typical grid-based capture. This approach would simplify the estimation of river bathymetry, as the flows and water levels during the LiDAR capture would be more temporally limited.

Hydraulic structure information was often excluded from regional scale modelling for a number of reasons. One of the key challenges associated with hydraulic structures is the impractical effort that would be required to define those structures within a 2D model at a regional scale. Furthermore, hydraulic structure databases may not be available, requiring extensive field survey or data collection to integrate the structures into the hydraulic models. One interesting approach to representing some conveyance associated with hydraulic structures was to hydro-connect the DEM. One approach considered hydro-connecting the DEM at culvert crossing locations by lowering the road elevation by the estimated widths of the culverts to the depth of the channel. While this approach overestimates the conveyance of the culvert crossings, it provides more

consistent hydraulic connectivity throughout the model domain. Furthermore, this approach can leverage road network and hydrologic network information to identify the location of crossings. This approach could also be supported by automation or machine learning. Another potential approach to estimating minor crossings could include assuming the size of the culvert or bridge crossing based on a simplified design flow related to the upstream drainage area, which could be automated. This approach could further be supported by machine learning to estimate the culvert invert elevation from available LiDAR data.

Limited observational data, including coastal, hydrometric and climate data station records were highlighted as a key data gap. Water level, flow data, and tidal stations datasets often include substantial data gaps, which is further exacerbated by the sparsity of the networks of those gauges. As well, hydrometric stations can experience operational failures during the passage of large flood events, or the stage-discharge relationships are extrapolated beyond measured data during severe flood events, affecting the uncertainty of those flow estimates. One potential approach to mitigating these data gaps is to regionalize the data, specifically relating historical flow records to topographic and / or meteorological indicators, which can then be used to infill missing records, or estimate flows in ungauged basins. Other data gaps that were highlighted included wind data, particularly in mountainous regions where winds are highly localized. Some input datasets have limited spatial coverage in Northern Canada.

Engagement with communities, including Indigenous communities, is important for understanding flood risk perceptions and incorporating community needs into mapping efforts. Traditional knowledge can also be valuable for infilling data gaps and understanding of historical flooding. As an example, regional flood mapping can aid in emergency management and cultural site protection. NRCan has developed guidelines for Indigenous engagement for flood mapping projects (NRCan, 2024c) which outline key principles of Indigenous engagement, roles and responsibilities, and the engagement process. This guidance recommends engaging communities early in the project to ensure that community needs or objectives and Indigenous Traditional Knowledge can be incorporated into project planning.

One process that was highlighted for consideration was that there should be guidance on pre-processing procedures for baseline data to be included in regional flood hazard models that is independent from the resulting modelling platform. In so doing, there would be much more consistency between different jurisdictional approaches to regional flood hazard modelling, as all approaches would be underpinned by consistent data.

5.1.2 COMPOUND FLOODING

Compound flooding and multiple drivers of severe flooding pose an additional layer of complexity for regional flood hazard modelling and mapping. There are a variety of flood mechanisms in Canada, as described in Section 2.0, which adds additional complexity in determining which flood event(s) or combination of flood events to analyze.

Discussions with different jurisdictions across Canada found that common approaches consist of focusing on a single flood mechanism for flood hazard modelling and mapping, generally the mechanism that results in the most severe flooding, or modelling and mapping flood mechanisms independently. However, engagement participants largely concurred that assessing compound flooding was important, and that there is a need for guidance on approaches to assess compound flooding.

Joint probability analysis and research has been considered in some jurisdictions. Some jurisdictions recommend combining prescribed annual exceedance probability (AEP) events (i.e., 50% AEP coastal and the 1% AEP riverine). Other approaches include looking at the causal mechanisms for floods at the onset of modelling to identify which types of floods or combination of events best cover the probability space. The historical probability of flood driving variables occurring together has also been assessed to estimate joint probability. Reviewing the historical record is recommended to ensure that no critical historical events or combinations of events were missed.

Composite maps, which overlay maximum extents from multiple flood mechanisms, such as river flooding, storm surge, and rainfall-driven flooding, are valuable tools for assessing compound flood risks. By visually combining the peak impacts of each mechanism, these maps help identify areas where multiple sources of flooding overlap or interact, highlighting zones of potential increased vulnerability. This integrated view supports risk assessments and emergency response, as it provides a clear representation of areas subject to compound flooding by pinpointing locations likely to experience the cumulative impacts of multiple flood sources.

One recommendation from the engagement sessions noted that there should be a pan-Canadian statistical study of coastal and fluvial compound flooding. This approach would provide a harmonized and consistent baseline understanding of compound flooding for the execution of flood hazard modelling and mapping studies throughout Canada, and could similarly be integrated into regional flood hazard modelling and mapping.

5.1.3 MODEL COMPLEXITY AND ADVANCES IN MODELING TECHNIQUES

The degree of model complexity being considered by the engagement participants for regional flood hazard modelling and mapping varied substantially, with approaches ranging from GIS based approaches to large-scale 2D hydraulic models. The suite of hydrologic and hydraulic models varied, although the HEC products from the U.S. Army Corps of Engineers (USACE) (i.e., HEC-HMS, HEC-RAS) was found to be a common solution, as the software has an existing broad user base familiar with the software, and it is also actively maintained by USACE. Other models, such as MIKE or TUFLOW, may be more suitable for flood hazard modelling at the regional scale or for automation. However, these programs require paid licenses.

Integrated surface water and groundwater modelling was being conducted using Aquanty's HydroGeoSphere as part of the Canada1Water project. Another innovative approach involved setting up the hydraulic modelling in tiles to run sequentially to reduce model simulation times. As noted in Section 4.0, this was implemented as part of the Info-Crue program using customized software to serialize the HEC-RAS models.

In general, 2D hydraulic modelling was generally recommended as the basis for pluvial and fluvial flood hazard assessments. For fluvial flood hazard assessments at a regional scale, 2D models were recommended to have varied mesh resolution, with lower resolution in areas located outside of the anticipated flood hazard zones, and increased resolution near the main waterways and developed areas. Similarly, for pluvial flood hazard assessments, 2D rain-on-grid modelling approaches were recommended for regional flood hazard modelling. Stochastic weather generation, such as USACE's Stochastic Storm Transposition method, were highlighted as approaches to better understand the potential impacts associated with variability in the historical tracks of storm events, and could provide a better understanding of pluvial and fluvial flood hazards.

5.1.4 GEOGRAPHIC SCOPE

Canada is a vast country with diverse landscapes, climates and exposed to a wide range of flood mechanisms, which poses significant challenges for flood modelling and mapping. Preliminary considerations must be made to define the geographic scope for any regional flood modelling initiative, including the assessment of prevalent flood mechanisms, the regional variability of the terrain, the distribution of the populated areas, the envisaged modelling approach, and the end-use of the mapping product. Canada also has several transboundary watersheds, which span multiple jurisdictions between provinces/territories and into the United States. Transboundary watersheds require additional considerations for the compilation of harmonized data.

Regional flood modelling and mapping presents different challenges depending on the characteristics of the terrain. On an island, such Prince Edward Island, due to its exposure to pluvial, fluvial, and coastal flood mechanisms, there is a need to assess each of those flood hazards to ensure a firm understanding of potential hazards. In very flat environments, small variations in the flood models can have significant influence on the derived flood maps. Mountainous terrain models may be less sensitive to model variations, but will pose other challenges, such as the description of complex flow pathways during intense rainfall events.

In some contexts, global flood modelling tools like Catchment-based Macro-scale Floodplain (CaMa Flood) have shown good results. The integration of global-scale tools and data with locally available information was identified as an approach to enhance regional planning and risk assessment efforts. However, it has also been noted that one of the challenges with larger scale modelling and mapping is the consistency of the results with smaller scale assessments and/or local knowledge and observations at a community level.

5.1.5 CLIMATE CHANGE UNCERTAINTY

There is a general recognition of the importance of considering climate change scenarios as part of regional flood modelling and mapping. However, while working with clearly defined SSP scenarios, there are multiple sources of uncertainty (ex. various models, scenarios, projections, future time horizons, parametrizations, etc.) associated with climate changes which should be understood, documented, and communicated as part of the mapping product.

One approach that was highlighted to inform the uncertainties associated with climate change projection is the adoptions of ensemble analysis techniques. This involves running multiple scenarios based on different climate models and SSP scenarios to capture the range of possible outcomes and incorporate statistical analysis of the simulated ensemble. To support this approach, leveraging existing large scale climate products based on standardized projections provides a robust and reliable foundation to generate future flood risk models, helping to account for variations in intensity and duration of climate change impacts.

In the context of extreme conditions, it was noted that the uncertainty in flow rates during regulatory flood events (i.e. 100-year horizons) could be significant and not often documented. This uncertainty can be comparable to the uncertainty of hydraulic models. Finding the right balance between the efforts invested in the estimation and quantification of the uncertainty and the model development to represent the relevant mechanisms confidently is important.

It was also highlighted that hydrological processes that were historically assumed to be static, but are now changing due to climate change (ex. permafrost, glacial melt, etc.) cannot easily be represented in

hydrological modelling software, as they assume that the parameterization of those processes is not dynamic. This limitation poses significant challenges for assessing hydrological processes in northern climates under both current climate and climate change conditions.

5.1.6 MODEL CALIBRATION AND VALIDATION

The importance of some level of model calibration and validation to build trust in the results of regional modelling was underscored in the engagement sessions. Some form of model verification was recommended, even where hydrometric data is not available for larger flood events. The availability of hydrometric records for model calibration and validation was repeatedly raised as a key challenge for modelling.

Simulated flow reanalysis data was raised as one method to fill this data gap. In Quebec, the HYDROTEL hydrological model was ran for each watershed 100 km^2 or greater. Ongoing work at the Environmental Forecasting Research division of ECCC involves applying reanalysis climate data to the GEM Hydro hydrologic model at a 1 km resolution. Streamflow reanalysis data from this model will be available for approximately half of Canada's watersheds at an hourly time step. However, this model is not calibrated and therefore there is less confidence in the model outputs in ungauged areas, but nonetheless could serve as a high level check on hydrological analyses.

Regional hydrologic approaches to estimate flows in ungauged basins for calibration and validation were raised. Remote sensing data, such as satellite imagery was also recommended as an approach to bridge some of the gaps in hydrological data. However, remote sensing data may not be available during the passage of flood events of interest due to inclement weather conditions that typically accompany these floods. It was noted that some jurisdictions and the Emergency Geomatics Service (Government of Canada, 2018) aim to capture satellite imagery during flood events as an approach to define historical flood extents, although the temporal availability of satellite tasking will likely mean that the peak flow is only captured for a portion of the flooded area, with either the rising or falling limb represented elsewhere in the imagery capture.

Other approaches that were highlighted to supplement model calibration and validation where there is limited data included the surveying of high water marks from previous floods. Local and traditional / Indigenous knowledge, including personal accounts, photographs, and records, about past flooding levels and extents was also recommended to fill data gaps. When both regional and detailed model results are available, comparisons should be made to benchmark and validate the performance of regional models.

5.1.7 ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

Regarding Machine Learning (ML) and Artificial Intelligence (AI), there is a general recognition of the promising and potential benefits of integrating these innovative technologies to support regional flood modelling and mapping.

Despite the rapidly growing interest and research on employing AI techniques in flood modelling, participants to the environmental scan indicated that it might be premature to fully envisage the integration of these technologies in a standardized approach. It was also noted that government regulations and restrictions can impact the use of AI in flood modelling, potentially limiting access to certain datasets or imposing constraints on the methodology.

One of the main comments on the use of AI for hydraulic modelling is that it is seen as an opaque black box and there is still a strong conviction that physics-based models are needed to understand the physical processed involved in the flooding mechanisms. Future developments in Explainable AI (XAI) may mitigate concerns regarding the black box nature of existing AI models, as the objectives of XAI is to help understand the steps and mechanisms under which an AI model arrives at a given conclusion or output.

Participants highlighted that AI techniques require extensive training datasets to develop a functional and representative tool. However, training datasets are often limited or even nonexistent, especially in the context of regional modelling. On the other hand, once trained, AI can be seen as a tool to complement existing datasets or to automate certain processes within hydraulic modeling, such as detecting river channel width from features like LIDAR point clouds, which could enhance the accuracy and details of flood modelling and mapping. AI models can also be used for either the generation of ensemble datasets for inclusion in physics-based modelling, or for the actual execution of ensemble simulations, depending on the context of the AI model.

One participant noted that AI was found to considerably outperform physics-based hydrologic models, and as such suggested that they strongly be considered in a regional setting. However, care must be taken to avoid extrapolating AI models beyond the datasets on which they were trained, as recent research has highlighted that these models suffer from poor extrapolation performance (Muckley et al., 2023).

In real-time flood modeling, AI models enable rapid simulation of flooding events, as highlighted in the comprehensive literature review conducted on the use of artificial intelligence in flood applications (Simonovic, 2024). Their shorter runtime provides a key advantage over physics-based models, which often face challenges in delivering precise results quickly.

AI techniques are seen as potentially useful for comparative analysis of simulations, particularly in understanding the correlation between climate factors and flood mechanisms, which may not be practical through traditional methods.

5.1.8 REMOTE SENSING AND EARTH OBSERVATION

Remote sensing, and particularly Earth Observation products, already provide significant support for flood modelling and mapping. In a regional modelling context, these techniques are particularly relevant, where access to locally gathered data may be limited either by the absence of immediate necessity or challenges in obtaining data from remote and inaccessible regions.

The Government of Canada hosts open data available both internally and for the public, via the Open Government Portal (i.e. https://search.open.canada.ca/opendata/). At the Canada Centre for Remote Sensing (CCRS), a division of the Canada Centre for Mapping and Earth Observation (CCMEO), NRCan's Emergency Geomatics Services (EGS) uses satellite-derived Earth observation imagery to actively monitor spring ice break-up and flooding and provide accurate, near real-time river ice state and open water flood extent maps to support emergency response activities.

Among the upcoming earth observation products, the Surface Water and Ocean Topography (SWOT) Mission and SWOT River Database (SWORD) have generated considerable interest for potential use for various aspects of food modelling and mapping. It is seen as a potential opportunity for understanding watershed scale flooding. Practically, the SWOT mission can provide an estimate of the water levels in lakes and SWORD

data can provide an estimate of water levels in rivers, serving as artificial hydrometric stations with a lower temporal resolution. This data can be used to support the calibration of fluvial flood hazard models by increasing the spatial coverage of hydrometric information.

Another important upcoming remote sensing-derived product is the Medium Resolution Digital Elevation Model (MRDEM), which will provide Canada-wide topographic coverage. The MRDEM is derived from the Copernicus DEM, which included edits to the WorldDEM, a global DEM created based on radar satellite data. Further modifications to the Copernicus DEM as part of the development of the MRDEM included the removal of buildings and forest canopy. The resolution of the MRDEM is 30 m by 30 m, and has been found to provide a considerably improved representation of ground surface elevations relative to the Canadian Digital Elevation Model (CDEM) (NRCan, 2024b).

5.1.9 LICENSING OF DATA AND OPEN DATA INITIATIVES

The access to environmental data, including open-source datasets, is facilitated by the increasing number of data portals being developed for the collection, presentation and dissemination of environmental datasets. Open-source datasets are immediately beneficial for flood modelling and mapping, as they can support the development of large-scale flood hazard models. Furthermore, the aggregation and dissemination of large datasets of environmental data is expected to provide valuable resources for AI techniques as they mature.

However, it was also noted that open data initiatives should be carefully managed to maintain the quality and relevance of dataset. The establishment of a framework for hosting, documenting and improving the dataset, the maintenance of platform as well as the provision of training to the potential user would support the integrity of the database. As well, many large-scale datasets lack adequate clarity for practitioners to readily access and work with those datasets. Improved clarity in communications for accessing those datasets would facilitate adoption and use of large-scale datasets by flood hazard modelling and mapping practitioners.

During the environmental scan, a vision has been shared regarding the potential benefits of public engagement to validate the simulated flood extents and levels defined by regional flood hazard modelling and mapping. Given the publication of flood modelling and mapping at a regional scale, individuals could provide feedback on the precision of the results, based on local observations. This approach could hypothetically lead to the validation of the model and mapping at a much broader regional scale and could lead to enhancements in the accuracy of flood hazard mapping in data sparse locations. However, it was noted that this approach could lead to a perception that initial models are inaccurate, and result in a deteriorated public confidence in the regional modelling approach.

5.2 Other Common Themes and Questions

In addition to the overall themes summarized in Section 5.1, a number of additional themes and questions were identified during the stakeholder engagement sessions. These included:

- A clear definition of the geographic scope associated with regional modelling must be communicated to practitioners and end users. Similarly a clear definition of the different approaches to modelling should be communicated, as well as the anticipated level of accuracy and use cases associated with those approaches.

- The appropriateness of the flood hazard maps for regulatory uses must be clearly defined, considering the precision of the topographic data, modelling methods, and the intended level of regulation.
- Engagement participants noted that clarity should be provided which flood events should be considered in the regional flood hazard mapping. It was also highlighted that ensuring consistency in simulated scenarios between jurisdictions would allow for easier comparison of flood extents between those jurisdictions.
- There was strong agreement that climate change should be considered in the regional flood hazard assessments. Once suggestion was that, rather than defining return periods to be simulated under climate change conditions, simulations instead focus on graduated forcing, which could then be related back to return periods. This would minimize near-duplication of simulations between current climate and climate change conditions, as there is often overlap between current climate and climate change scenarios.

6.0 RECOMMENDATIONS FOR CONSIDERATION IN REGIONAL FLOOD MAPPING GUIDELINES

6.1 General Recommendations

The following general recommendations were identified as part of the environmental scan for inclusion in regional flood hazard modelling and mapping guidelines:

- Information should be provided regarding the anticipated level of accuracy associated with different approaches to modelling, and the data being used in the development and implementation of those models. Similarly, appropriate use cases should be defined and clearly communicated to practitioners and end users for each of those levels of accuracy.
- The process for data pre-processing should be standardized to ensure that consistent input data is provided to flood hazard models, regardless of the model being used. This approach results in a consistent baseline of information being used to develop regional flood hazard models between jurisdictions and practitioners.
- The guidelines should avoid being too prescriptive to respect the experience and expertise that has been developed throughout the various jurisdictions within Canada. However, some guidelines on standardization should be provided, such as the return period and climate scenarios being considered, such that there is consistency in the regional flood hazard models and maps across jurisdictions.
- Regional flood hazard modelling and mapping should maximize the use of automation to ensure that the level of effort required to develop those models and maps is commensurate with the expected accuracy and usefulness of those products.
- Flood protection infrastructure, such as dikes, dams, and floodwalls protect a significant number of Canadian communities. As such, it is critical to ensure that flood protection infrastructure is accurately represented the hydraulic model. The basis for defining the flood protection infrastructure should be defined in the model based on the best available information, such as LiDAR, design drawings, or field survey data.
- Uncertainty in the data and analyses considered in regional-scale flood hazard modelling and mapping should be evaluated and qualitifed as best as possible, and disseminated as part of the resulting reporting and mapping products.

6.2 Fluvial Flooding

Based on the information obtained as part of the environmental scan, and the general consensus among the engagement participants, fluvial flood hazard modelling at a regional scale should include the following considerations:

- The topographic data integrated into the definition of the flood hazard modelling should be the best possible data available, with a strong bias towards LiDAR data. However, for applications where lower resolution data is used, the potential impacts to the accuracy of the resulting flood hazard delineation, as well as the appropriate use cases, must be communicated.

- The approach taken for fluvial flood hazard modelling should consist of 2D hydraulic modelling using appropriate modelling software, as this approach best leverages computational advances in flood modelling, and can be flexibly adapted based on available data. The use cases and anticipated level of accuracy associated with the selected modelling approach must be clearly communicated to end users to ensure in conjunction with the communications regarding the anticipated accuracy associated with the topographic data.
- Specific considerations for flood hazard delineation based on 2D hydraulic modelling include:
  - The approach taken to defining the hydrological inputs to the model should be based on regional preferences, including regional flood frequency analyses or hydrologic modelling.
  - Hydraulic models should, as best as possible, extend to cover full watersheds, and not be limited to jurisdictional boundaries. This approach minimizes any assumptions related to the distribution of flooding along those jurisdictional boundaries. Furthermore, depending on local expertise and expert judgement, minor tributaries should be included to the fullest extent feasible. However, depending on the scale of the model, it may be necessary to neglect tributaries with drainage areas less than a given threshold.
  - Channel bathymetry should be estimated following the methods developed by the University of Concordia, or design flows should be reduced to account for the in-channel flows that were apparent during the LiDAR capture. These approaches have been shown to significantly improve model accuracy. Using LiDAR directly may be appropriate for shallow streams. However, expert judgement and local expertise will be required to determine the most appropriate approach.
  - Remote sensing data, such as land use classification data, should be used to define initial estimates of model parameters, such as roughness coefficients.
  - Existing detailed hydraulic models or model results should be used to support regional-scale model development, or could serve as boundary conditions to those regional-scale models.
- GIS-based and hydraulic modelling methods should be calibrated and validated as best as possible. In addition to any available hydrometric data, the calibration could also include:
  - Remote sensing data;
  - Surveyed high water marks;
  - Local and Indigenous knowledge.

6.3 Pluvial Flooding

While there has thus far been a relatively limited implementation of pluvial flooding on a regional scale, a number of considerations were generally agreed to be reasonable with the engagement participants, and should be considered in guidance documents for regional flood hazard modelling. These considerations include:

- Pluvial flood hazard modelling should be completed using 2D rain-on-grid modelling. This approach provides the best spatial representation of overland flooding due to rainfall events. However, the differences between pluvial flooding and fluvial flooding must be clearly communicated to end-users, and additional information, such as simulated flood depths, should be provided in conjunction with flood hazard extents. This will serve to further highlight the fundamental difference in flooding due to pluvial versus fluvial causes. Furthermore, the feasibility of implementing rain-on-grid modelling at a

regional scale are likely limited by computational resources, and thus should only be implemented in select areas withing a broader regional hydraulic model, such as in populated areas within the watershed, or areas with a history of pluvial flood hazards.

- Similar to fluvial flood hazard modelling, pluvial modelling should be based on the best available topographic data, with a strong bias towards LiDAR data. Uncertainty in the flood hazard extents associated with the topographic data used in the hazard delineation should be clearly communicated.
- Where possible, bathymetry along major waterways should be estimated using the same methodology as described for fluvial flooding. Similarly, the hydrologic network should be integrated into the DEM to ensure hydraulic connectivity throughout the model domain.
- Integrating all culvert and bridge crossings into the model likely will not be feasible. Instead, major river crossings should be integrated into the DEM. Culverts could similarly be represented by simplified modifications to the DEM based on the culvert geometry, although consideration must be given to the resolution of the DEM as coarser DEMs would significantly overestimate the conveyance of the structures. Alternatively, some hydraulic models allow for the definition of culvert structures as in-line structures that use empirical equations to estimate flows. The size of these structures can be estimated by developing assumptions relating the upstream drainage area, crossing type, and assumed design flow event to estimate the design flow of the structures. Depending on the model type, scripting can be developed to automate the definition of these culvert crossings for integration into the model.
- Rainfall events considered in the pluvial flood hazard model should consist of relevant design storm events, based on jurisdictional guidance. Stochastic weather generation approaches could be implemented to vary key parameters associated with the design storm, such as intensity, timing, and spatial track of the simulated storms. This approach can provide an understanding of the model sensitivity to key characteristics of the storm, and also define the most conservative pluvial flood hazards based on the stochastic analysis.
- Geospatial data, such as land use classification and soils data, should serve as the basis for defining infiltration parameters in the rain on grid model. Adjustments to the infiltration parameters may be warranted to represent processes not well represented by the model, such as evaporation and transpiration.
- Similarly, modifications to rainfall data in urban areas may be a suitable simplification to represent stormwater infrastructure in those urban areas. This could include reducing the precipitation in urban areas by the design rainfall amount that the stormwater systems were designed to safely convey, or a conservative assessment of the service capacity based on local experience.
- Pluvial flood models should be calibrated as best as possible to available data, including hydrometric data, remote sensing data, high water marks, and local and Indigenous knowledge, as appropriate.

6.4 Coastal and Lakeshore Flooding

From the various case studies, interviews and background literature and research, it is feasible to establish a consensus as to which coastal processes should be considered when assessing regional coastal flood hazards. Based on the various lines of evidence presented herein and discovered throughout this environmental scan, it is proposed, that at a regional scale, the following processes be considered for coastal flood hazard modelling:

- **Storm surge**, where extreme water levels can be interpreted regionally using 2D numerical modelling tools, or a dense network of observations, which can generate a long-term hindcast (i.e. > 50-years) of atmospheric residuals or total water levels. Statistics can then be used to derive the variable AEP of the residual or total water level along the regional shoreline of interest. Alternatively, the surge from individual events, or synthetic storm events, can be simulated where the target water level has a known AEP. This approach is particularly relevant when assessing storm surge associated with tropical storms, hurricanes or cyclones, which often require dedicated modelling efforts.
- **Joint probability of surge and high tidal levels**. In tidal environments, it is generally recommended to consider total water levels (combination of tide and storm surge) when assessing the AEP of a coastal flood water level.
- **Modelling storm surges and tides together** (i.e., including tide-surge interaction) has been shown to be important locally on the east coast (Bernier and Thompson, 2007).
- **The effects of density variation** have important seasonal, subseasonal and interannual contributions to the sea level variability, particularly on the west coast (Wang et al., 2022; Han and Lu, 2023). It also affects short-term processes like storm surge although it is very local, such as over narrowing shelves.
- **Sea ice can modulate tides and suppress storm surges**, and it needs to be considered in the Canadian Arctic (Wang and Bernier, 2023).
- **For regional storm surge modelling**, the domain needs to sufficiently large to include remote contributions, since coastal trapped waves, forced by storm surges, can travel thousands of kilometers.
- **Lake seiching and set-up**. Shallow lake systems can experience significant seiching and set-up, increasing flood risk locally along shoreline exposed by prevailing and sustained winds. This process must be captured on large lake systems such as Lake Erie and Lake Winnipeg.
- **Wave energy gradients over larger distances**. Regionally, wave hazards can be considered at a descriptive level of detail, using regional modelling tools, where wave hazards and exposure can be characterized for a screening level assessment.
- **Assessment of wave hazards for selected locations**, on a case-by-case basis, to account for site-specific wave run-up and set-up. In general, an assessment of detailed wave hazards is not practical to incorporate in regional flood hazard assessments. Wave hazards should be considered selectively and interpreted at priority sites only for mapping purposes.
- **Tsunamis are inherently a regional process**, as they generally impact large areas. Flood hazards associated with tsunamis are generally well studied along Canada's west coast, and a strong body of literature, research, mapping efforts, and studies is publicly available to characterize tsunami hazards. To complement literature in less documented areas and/or where tsunami frequency and is estimated to be lower, such as in Eastern Canada, flood hazard modelling of tsunamis can be conducted using the internationally recognized NTHMP guidelines and input from a seismic expert.
- **Future flood hazards associated with sea level rise and other climate change impacts** should leverage existing and ongoing research, studies, and modelling initiatives to incorporate the latest knowledge available. Information on climate change and its impacts on coastal flood mechanisms is updated rapidly based on regular updates from IPCCC, on the availability of new large-scale models and on the occurrence and observations of extreme (and potentially unprecedented) events.

Flood hazards associated with changing shoreline features and profiles due to erosion, loss of shoreline vegetation and habitat, permafrost losses, compound flooding in estuaries (with the exception of very large systems such as the Fraser River and Mackenzie Delta systems), and geohazards such as tsunamis generated by landslides, should be considered as local processes, which are more challenging to characterize and investigate at regional scale. Thus, it is recommended to identify these processes as potential contributors to coastal flood hazards in a regional assessment, and to investigate these further in greater detail when conducting a site-specific or detailed coastal flood hazard investigation.

6.5 Compound Flooding

The following considerations should be considered for addressing compound flooding in a regional flood hazard modelling context:

- Compound flooding should be considered in regional flood hazard modelling and mapping as best as possible. A number of flood mechanisms can readily be integrated into a cohesive estimate of overall flood hazard, such as combined coastal and pluvial or fluvial flood hazards. However, the joint evaluation of pluvial and fluvial flood hazards may result in mapping products that are difficult for end users to interpret, and as such should be considered separately.
- The occurrence of compound flooding should generally be simplified to assume that flood mechanisms are either statistically colinearly dependent, or statistically independent.
- A national study of compound flooding should be completed to provide a uniform basis for evaluating compound flooding across jurisdictions. This would ensure consistency in the assumptions relating to compound flooding.

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APPENDIX A

Stakeholders Engaged for the Environmental Scan Interviews

TABLE A-1: SUMMARY OF ENVIRONMENTAL SCAN INTERVIEWS

Date	Organization	Personnel	Relevance
February 13, 2024	Government of Alberta (Environment and Parks)	Bryce Haimila Peter Onyshko Jane Eaket Hammad Javid	Provincial agency responsible for flood mapping.
February 15, 2024	Aquanty Inc., Geological Survey of Canada	Steven Frey Eric Kessel Hazen Russell	Canada1Water
February 15, 2024	Public Safety Canada	Julie van de Valk Robin Bourke	Procured several Canada-wide global flood hazard models.
February 15, 2024	University of Prince Edward Island	Xander Wang Quan Dau Farhan Aziz	Province-wide pluvial flood modelling
February 22, 2024	Ebbwater Consulting	Silja Hund	Regional pluvial, fluvial, and coastal flood hazard mapping expert
February 22, 2024	Government of Quebec Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs	Simon Rochette François Larouche-Tremblay Gabriel Roy-Poulin	Info-Crue
February 23, 2024	Concordia University	Pascale Biron Guenole Chone	Channel bathymetry estimation approach
February 23, 2024	Environment and Climate Change Canada	Mercè Casas-Prat Pengcheng Wang Joshua Wiebe	Large-scale storm surge modelling
February 26, 2024	Government of Newfoundland and Labrador Water Resources Management Division	Paula Dawe	Provincial agency responsible for flood mapping.
February 27, 2024	CBCL	Alexander Wilson Amaury Camarena	Consult on HRM flood hazard mapping
February 27, 2024	United States Army Corps of Engineers	William Lehman Gregory Karlovits Evan Heisman	Working on FEMA's Future of Flood Risk Data program

Date	Organization	Personnel	Relevance
		Michael Bartles Nick Lutz	
February 28, 2024	Government of Yukon	Cian O'Neill-Kizoff Holly Goulding	Territorial agency responsible for flood mapping.
February 28, 2024	Environment and Climate Change Canada	Etienne Gaborit Dorothy Durnford Vincent Fortin Silvia Innocenti Dikraa Khedhaouiria Marko Markovic Pascal Matte Joshua Wiebe	Streamflow reanalysis modelling
March 1, 2024	Federal Emergency Management Agency	David Rosa Rick Nusz Jamie Prochno Andrew Megrail Laura Algeo	Base Level Engineering
March 1, 2024	National Research Council (Ocean, Coastal and River Engineering Research Centre)	Enda Murphy Julien Cousineau Ali Khan	Large-scale coastal models, regional fluvial modelling
March 4, 2024	Government of British Columbia	Sarah Simon Kate Forbes	Provincial agency responsible for flood mapping.
March 5, 2024	Deltares	Anaïs Couasnon David Casson	Experience with local/global scale modelling.
March 5, 2024	Queen's University	Ryan Mulligan	Regional coastal modelling.
March 6, 2024	BGC Engineering	Patrick Glover Kris Holm	Large scale flood hazard modelling
March 8, 2024	Government of Nova Scotia	Peter Bishop Daniel Bryce	Developing a regional flood hazard modelling methodology.
March 8, 2024	Western University	Slobodan Simonovic Mohammad Reza Najafi	Canada-wide flood hazard modelling.

Date	Organization	Personnel	Relevance
March 12, 2024	Federal Emergency Management Agency	Lauren Schmied	Regional coastal modelling
March 12, 2024	Northwest Hydraulic Consultants	Dale Muir	Experience with detailed floodplain mapping
March 20, 2024	University of Waterloo	James Craig Bryan Tolson	Raven hydrologic modelling platform
April 17, 2024	Government of New Brunswick	Achraf Hentati	Regional inland and coastal flood hazard modelling
May 1, 2024	Natural Resources Canada	Heather McGrath Nicky Hastings	Regional coastal modelling, flood susceptibility index

APPENDIX B

Summary of Projects

TABLE B-1: OVERVIEW OF REGIONAL FLOOD HAZARD MODELLING PROJECTS

Project Name	Location	Year	Funding Source	Flood Mechanisms	Size	Modelling Methods	Key Assumptions	Resolution
Canada1Water (Kirkwood, 2023)	Canada-wide (including transboundary watersheds)	Version 2.0 released Spring 2024	Canadian Safety and Security Program – Defence Research Development Canada, Geological Survey of Canada – Natural Resources Canada, Agriculture and Agri-Food Canada, Aquanty Inc., and the University of Toronto and University of Waterloo (via NSERC support)	Fluvial, pluvial	11.8 x 10^6 km^2	HydroGeoSphere surface-groundwater model	N/A	The 4th order C1W model (standard C1W) is discretized with 1,000 m for edge along streams, 2,000 m elsewhere, to a maximum of 5,000 m.
PEI Pluvial Modelling	Prince Edward Island, subdivided into three models	Ongoing	Prince Edward Island, NRCan (FHIMP)	Pluvial, coastal	Province-wide	HEC-RAS 2D	Hydro connected DEM, no hydraulic structure data or bathymetry. Modified rainfall approach to represent effect of stormwater infrastructure in urban areas.	10 m with 2 m refinements for main cities/communities 100 m with 20 m refinements elsewhere
Info-Crue (MELCCFP, 2024)	Quebec	N/A	Provincial grant	Fluvial	50 watersheds in Quebec, approximately 8,000 km of lineal river length	HYDROTEL HEC-RAS 2D	Estimated bathymetry, model subdivided into smaller domains and simulated in series	8-32 m in the floodplains
Concordia University Case Study	Southwest Miramichi	N/A	NRCan	Fluvial	250 km^2	HEC-RAS 2D	Bathymetry estimation from LiDAR, no hydraulic structure data	N/A
Regional Storm Surge and Wave Modelling (KGS Group, 2023)	Newfoundland & Labrador	2024	Newfoundland and Labrador, FHIMP	Coastal	Province-wide	MIKE21 FM HD, MIKE21 FM SW	Climate Change modelling for 2 different GCMs, No wave setup nor wave runup	down to 1.5km
Halifax Regional Municipality Flood Mapping (CBCL, 2023)	Halifax Regional Municipality, subdivided into 27 sub-watersheds	2023	N/A	Pluvial, fluvial, coastal	5,475 km^2	PCSWMM (integrated hydrological-hydraulic model) MIKE21	Partial data for hydraulic infrastructure, analysis did not consider wave run-up, ice jamming or debris jamming	1-10 m

Project Name	Location	Year	Funding Source	Flood Mechanisms	Size	Modelling Methods	Key Assumptions	Resolution
Yukon River Basin Streamflow Forecasting System (Elshamy et al., 2020)	Yukon	2020	Natural Disaster Mitigation Plan	Hydrologic	Main Yukon Basin (288,000 km^2) and Porcupine River Basin (58,900 km^2)	MESH	Model driven by GEM-CaPa data for hindcasts and GEM ECCC RDPS / GDPS forecasts	Simulated at both 10 km and 5 km
National Surface and River Prediction System	Half of Canadian watersheds	N/A	N/A	Hydrologic	Mackenzie, Nelson-Churchill, St. Lawrence, Yukon River, Columbia River, Skeena River, and Bay of Fundy watersheds	GEM Hydro hydrologic model (SVS and WATROUTE)	No calibration	1 km
Base Level Engineering (FEMA, 2022)	United States watersheds	Ongoing	FEMA (US)	Fluvial	Watersheds throughout the US	HEC-RAS 1D, HEC-RAS 2D	Automated modelling, complete LiDAR coverage, limited hydraulic structure data	N/A
Coastal Modelling	Continental United States coastline	NA/	FEMA (US)	Coastal	Populated continental US coastline	STWAVE and coupled ADCIRC SWAN model	N/A	N/A
Western University Global Riverine Modelling (Mohanty & Simonovic, 2021)	Canada-wide	N/A	N/A	Fluvial	Canada-wide	CaMa-Flood	N/A	1 km
New Brunswick (Laroche et al., 2020)	New Brunswick (inland, excluding St. John River)	2020	National Disaster Mitigation Plan	Fluvial	N/A	HEC-RAS 2D	Synthetic unit hydrographs developed using GIS based tool, DEM processed to burn in some hydraulic structures, some culverts added manually (i.e., in urban areas), no bathymetry.	Ranged from 5 m to 45 m

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