Next Generation Flood Model for Canada: A Comprehensive Approach by Impact Forecasting

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ABSTRACT

Flooding is one of the most consequential natural hazards in Canada, regularly causing major economic losses. Catastrophic events in Alberta and Ontario in 2013 or in British Columbia in 2021 highlight the need for advanced, physically based and climate-aware flood risk tools for the insurance sector and others. Impact Forecasting, Aon's catastrophe model development center, has been developing a dedicated flood model for Canada since 2015, with successive updates including a pluvial component and a climate change view. The latest generation, Impact Forecasting Flood Model for Canada 3.0, is a complete rebuild using new datasets and modelling approaches. It covers the entire Canadian territory of roughly 10 million km²; integrates fluvial and pluvial flooding and storm surge. Hazard and vulnerability components are combined with detailed property information to estimate losses at high spatial resolution.

Flood maps are derived from large sets of 2D hydrodynamic simulations using high-resolution Digital Elevation Models with grid resolutions from 0.5m to 10m in areas containing over 95% of the population, complemented by 30m MRDEM and 2m ArcticDEM elsewhere. Simulations are performed in TUFLOW, producing flood depths, velocities at resolutions up to 5m. Hydraulic conditioning of DEMs includes artefact removal and explicit representation of channels and defenses, while pluvial simulations account for variable rainfall intensities, soil infiltration properties and urban stormwater drainage.

An atmospherically driven stochastic event catalog combines pluvial and fluvial events derived from long-term rainfall–runoff simulations. Forcing data include historical reanalyzes and CMIP5/CMIP6 climate model runs, which are bias-corrected and downscaled using machine learning to produce thousands of years of daily precipitation and temperature for present and future climates. The HYPE rainfall–runoff model is calibrated for Canadian conditions, including prairie hydrology, snow processes and ice jams, to generate stochastic river flows. In parallel, a storm surge component based on the SFINCS model simulates coastal and Great Lakes flooding from cyclone-driven events, enabling a consistent representation of multiple flood drivers within a single catastrophe modelling framework.

KEYWORDS: flood risk; Canada; fluvial flooding; pluvial flooding; storm surge; climate change; catastrophe model; hydrodynamic modelling

1 INTRODUCTION

Flooding is one of the most damaging natural hazards in Canada, causing large economic losses and social disruption. Recent events, such as the 2013 floods in Alberta and Ontario, the 2021 floods in British Columbia, and the 2024 floods in Quebec, have shown that Canadian flood risk is driven by multiple mechanisms, including river flooding, intense rainfall, snowmelt, ice jam and storm driven events. These events underline the need for physically based and climate aware tools to support flood risk management and decision making, especially in the insurance and reinsurance sectors.

Impact Forecasting, Aon's catastrophe model development center, has maintained a dedicated flood model for Canada since 2015. The original version focused mainly on fluvial flooding and was gradually enhanced by adding a pluvial component and a climate change view. However, advances in topographic data, hydrological and hydrodynamic models and climate information have created both the opportunity and the need to redesign the model more fundamentally.

The Impact Forecasting Flood Model for Canada 3.0 represents this next generation step. It is a complete rebuild that combines new high resolution Digital Elevation Models (DEMs), updated 2D hydrodynamic simulations and an atmospherically driven stochastic event catalog. The model covers the entire Canadian territory of about 10 million km² and explicitly represents fluvial and pluvial flooding and storm surge along the coasts and the Great Lakes. Hazard and vulnerability components are designed to be used with detailed property exposure data to estimate flood losses at high spatial resolution.

The aim of this paper is to present the methodological framework and overall architecture of the Impact Forecasting Flood Model for Canada 3.0, rather than to provide a full quantitative evaluation. We describe how the different hazard components are modelled, how long climate simulations and rainfall–runoff modelling are used to construct a stochastic event catalog, and how these elements fit within a catastrophe modelling context. Selected illustrative hazard outputs are shown, while full calibration and validation are left for future work.

2 MODEL ARCHITECTURE AND COVERAGE

The Impact Forecasting Flood Model for Canada 3.0 follows a standard catastrophe modelling structure (Figure 1). It combines a hazard component, representing physical flood processes, with a vulnerability component describing damage to exposed assets and an exposure component describing the spatial distribution and characteristics of insured property. Together, these components provide probabilistic estimates of flood losses for individual locations, portfolios and aggregated regions.

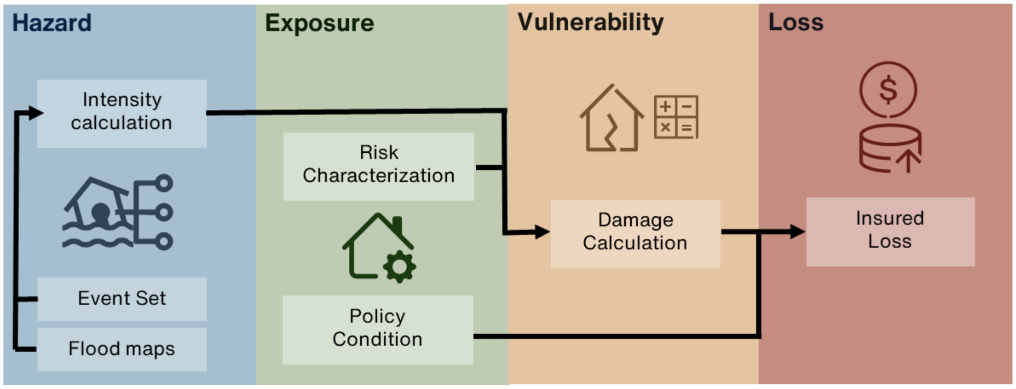

Figure 1: Scheme of catastrophe flood model

At the hazard level, the model integrates three main flood perils. Fluvial represents riverine inundation on the floodplain and in adjacent off floodplain areas. Pluvial flooding represents surface water accumulation driven by intense rainfall, including urban flooding where drainage capacity is exceeded. A storm surge component captures coastal and Great Lakes flooding caused by tropical cyclone driven events. All three components are built on a common terrain and hydrological basis.

The model covers the entire Canadian territory of approximately 10 million km². High resolution Digital Elevation Models HRDEM (Government of Canada, Natural Resources Canada, 2025) with grid resolutions between 0.5 m and 10 m are used in areas containing more than 95% of the population, enabling detailed representation of terrain, drainage features and flood defences. For the remaining areas, 30 m MRDEM (Government of Canada & Natural Resources Canada, 2025) and 2 m ArcticDEM (Morin et al., 2016) ensure full national coverage. Hydrodynamic simulations are run on these DEMs and hazard layers such as flood depths are generated at resolutions up to 5m, and can be aggregated to coarser resolutions when required.

On the loss side, hazard outputs are combined with regional and occupancy-specific vulnerability functions and detailed property exposure information. This allows the model to provide loss estimates for individual buildings where coordinates and attributes are available, as well as for aggregated administrative units. While this paper focuses on the hazard and event catalog components, the overall architecture in Figure 1 is designed to support end-to-end flood risk assessment across Canada.

3 HAZARD MAPS MODELLING METHODOLOGY

3.1 Digital Elevation Models and terrain processing

The hazard maps are modelled using HRDEM, MRDEM and ArcticDEM. All DEM sources are harmonized and converted to resolutions suitable for 2D hydrodynamic simulations, typically 5 m or 10 m. Before simulations, the terrain is hydraulically conditioned by removing artefacts, correcting artificial barriers and explicitly representing river channels, drainage features and known flood defenses. In urban areas, additional processing represents key conveyance elements such as canals, culverts and major overland flow routes, so that both fluvial and pluvial processes are consistently captured.

3.2 Fluvial flooding (floodplain and off-floodplain)

Fluvial hazard maps are based on a combination of hydrological analysis and 2D hydrodynamic simulations in TUFLOW (TUFLOW, 2025). Canada has a dense hydrometric network, with more than 7,000 discharge gauges in the national HYDAT database (Water Survey of Canada, 2025), particularly in populated regions. This network was used to perform frequency analysis of observed flows, derive design discharges for a range of return periods and characterize regional hydrological behavior. Several probability distributions were fitted at each station, including Lognormal (LN3), Gamma, General Extreme Value (GEV), Gumbel (GUM) and Weibull (WEI). To obtain design flows along the entire river network, graph theory concepts were applied to propagate and interpolate design discharges from gauged to ungauged basins. For ungauged catchments, hydrological similarity methods group basins based on multiple hydrological, topographic, morphological and climatological attributes and transfer information from better observed to data poor regions. The resulting design discharges provide consistent inputs for hydraulic simulations across the full model domain.

Hydrodynamic simulations in TUFLOW are then performed on the conditioned DEMs, using a Sub Grid Sampling approach (TUFLOW, 2025) that preserves fine scale terrain structure even when the computational grid is coarser, for example allowing 1m LiDAR information to be used in 5 m simulations. The fluvial component explicitly distinguishes between floodplain and off-floodplain areas. Floodplain maps represent direct river inundation for the design flows. The off-floodplain component captures damage mechanisms commonly observed in claims data outside the main inundation footprint, such as losses related to elevated groundwater levels causing seepage through basement walls or flooding caused by failure or absence of backflow protection on sewer connections. Information on flood protection measures, such as dikes and levees, and their indicative levels of protection is incorporated where available from municipalities or governmental sources, hydrological analyses or flood protection manuals, and complemented by automated ML detection methods where explicit defense data are limited.

3.3 Pluvial flooding

Pluvial hazard maps represent surface water flooding driven by intense rainfall events. Design rainfall is derived from intensity–duration–frequency (IDF) curves constructed using multiple datasets. Gridded products such as the Ensemble Meteorological Dataset for North America (EMDNA) (Tang et al., 2020a) are combined with station data from the Serially Complete Dataset for North America (SCDNA) (Tang et al., 2020b) and other Canadian sources to derive spatially consistent IDF curves across Canada. These curves provide design rainfall depths for a range of durations and return periods.

For hydrodynamic modelling, these IDF based design depths are converted into spatially distributed design storms using constructed hyetographs. A modified Chicago method (Keifer & Chu, 1957) is applied to generate temporal rainfall patterns consistent with the target IDF curves while concentrating peak intensities around a specified time within the storm. This allows the simulations to represent both total storm depth and realistic temporal clustering of intense rainfall, which is critical for pluvial flooding in urban catchments.

The same DEM as in the fluvial component is used, supplemented by land use and soil information that define spatially variable roughness and infiltration parameters. Infiltration is parameterized using soil and land surface datasets to distinguish between permeable and impervious areas and to reflect regional differences in soil properties. Pluvial simulations are carried out as 2D hydrodynamic simulations forced by the design storms and represent key processes such as infiltration, surface storage and runoff concentration. Urban stormwater drainage systems are represented in the model with assumption of the location of inlets, outlets and their capacity capturing the onset of surface flooding once system capacity is exceeded. The resulting maps quantify the depth and extent of pluvial flooding, which can be combined with fluvial and off floodplain components in an integrated hazard view.

3.4 Storm surge

Coastal and Great Lakes flooding driven by storm surge is represented using the SFINCS model (Leijnse et al., 2021). This component simulates water level setup and overland inundation associated with severe storms and cyclone driven events along the Canadian coasts and selected Great Lakes shorelines. The simulations use the same DEM as the fluvial and pluvial components, ensuring consistent representation of topography, coastal defenses and low-lying areas. Storm surge hazard layers are produced for a set of tropical cyclones used in the US hurricane model certified by the Florida Commission and are later linked to the inland flooding event catalog. This allows storm surge events to be considered together with fluvial and pluvial events in a unified catastrophe modelling framework and supports analyses of multiple flood drivers affecting coastal areas.

4 CLIMATE FORCING AND STOCHASTIC EVENT CATALOG

4.1 Atmospheric forcing data

The stochastic event catalog is driven by long, consistent time series of precipitation and temperature compiled from several climate and reanalysis products. To represent present day variability, a 50 year window from 1987 to 2036 is used wherever possible, yielding more than 10,000 simulation years of daily forcing in total. For future climate conditions, multiple SSP scenarios with time windows from 2030 to 2100 are used. As a physically based reference, the ERA5 reanalysis (Hersbach et al., 2020) provides a baseline reconstruction of historical precipitation and temperature fields. It is complemented by the Ensemble Meteorological Dataset for North America (EMDNA) (Tang et al., 2020a), a station based, reanalysis infused product that blends gauge information with large scale fields. To extend the range of climate conditions and scenarios, bias corrected and downscaled outputs from global and regional climate models are included, in particular the CanLEAD (Cannon et al., 2022) and CanDCS M6 (Sobie et al., 2024) ensembles and dynamically downscaled simulations from the NA CORDEX framework for North America (Mearns et al., 2017).

Figure 2: Example of HYPE–mizuRoute calibration at a selected HYDAT gauge, showing observed and simulated daily discharge and demonstrating the ability of the model to reproduce seasonal regimes and high-flow events.

4.2 Rainfall–runoff modelling

The hydrological transformation from precipitation and temperature to river flows is performed using the HYPE rainfall–runoff model (Lindström et al., 2010) with routing via the mizuRoute framework (Mizukami et al., 2016). HYPE is applied over the Canadian domain with parameterizations tailored to regional conditions, including prairie hydrology, snow accumulation and melt and other cold climate processes. Calibration is based on discharge observations from the national HYDAT network and other sources, with a focus on capturing both seasonal regimes and high flow behavior relevant for flooding and the insurance sector. An example of the calibration performance for one representative gauge is shown in Figure 2. The simulated hydrograph closely follows the observed discharge, capturing both the seasonal regime and individual high flow events, which is essential for reproducing the timing and magnitude of flood peaks relevant for hazard and loss modelling. The stochastic forcing is then run through the calibrated HYPE setup to generate long synthetic time series of river discharge along the river network. These simulations provide a consistent representation of hydrological variability and extremes under present and future climate conditions and form the basis for constructing the fluvial component of the stochastic event catalog. For selected regions and processes, additional hydrological components, such as ice jams, are incorporated where relevant to Canadian flood regimes.

4.3 Construction of the event catalog

The atmospherically driven stochastic event catalog is constructed by identifying flood relevant events within the long term hydrological and meteorological simulations. For fluvial flooding, candidate events are detected based on river discharge peaks exceeding specified thresholds or return period levels (RP 1 in 2 years with potential to cause insured losses) at locations across the river network, and spatial–temporal clustering algorithms group related peaks into basin scale or multi basin flood events. For pluvial flooding, events are identified from precipitation fields, focusing on high intensity and short duration rainfall critical for surface water flooding. Thresholds are applied to accumulated rainfall over relevant durations, and spatial clustering is used to define pluvial. The identification of pluvial and fluvial events is done together so that concurrent or causally related phenomena (e.g. storms producing both heavy rainfall and elevated river flows) are represented as combined events in the catalog. Each event in the catalog is associated with a set of hazard maps generated by hydrodynamic simulations.

4.4 Integration with storm surge events

Storm surge events are integrated into the same catalog to enable a multi-peril view of flood risk. For coastal and Great Lakes regions, cyclone-driven systems are identified within the climate and reanalysis datasets based on metrics such as low pressure, strong winds and elevated water levels. Stochastic catalog of TC events is used to drive SFINCS simulations of storm surge and coastal inundation, producing hazard layers that are linked to corresponding atmospheric conditions.

5 RESULTS AND DISCUSSION

5.1 Fluvial and pluvial flood extents

To demonstrate the capabilities of the fluvial component, Figure 3 presents an example of simulated flood extents and depths for a selected river reach in a densely populated area. The map shows a 1 in 100-year fluvial event derived from the hydrological frequency analysis.

The final flood extents highlight several key features of the model. High resolution terrain allows floodplain geometry, local depressions and flow paths to be represented in detail, which is reflected in the spatial variability of flood depths near the channel and in adjacent low-lying areas. The inclusion of flood protection measures is visible in the way defences constrain or redirect inundation. These aspects are essential for reproducing observed claim patterns during large river floods. In addition, the same combination of high-resolution terrain, spatially variable infiltration and an aggregated representation of stormwater drainage leads to realistic patterns of urban flooding. Water accumulates in local depressions, behind transport embankments and along streets that act as flow conduits, and even where river flooding is minor, pluvial processes can generate significant surface water depths and associated losses.

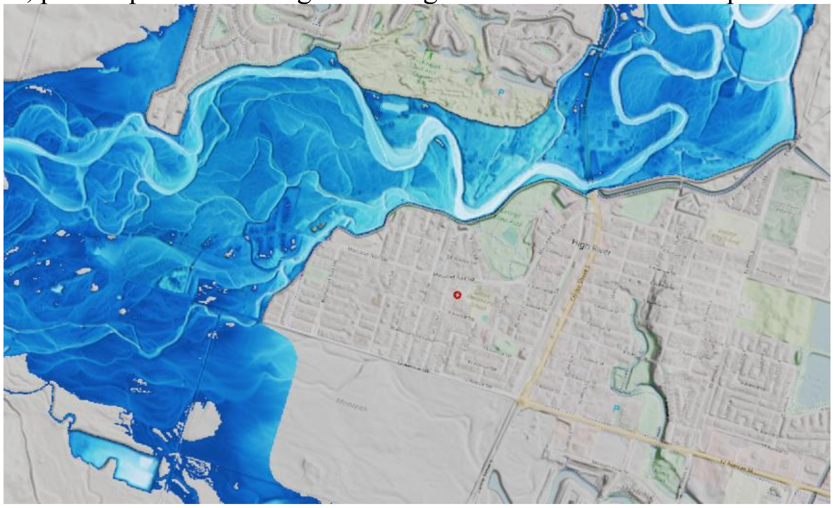

Figure 3: Example of simulated fluvial flood depths for return period 1 in 100 years, close to High Rivers with all design protection included in simulation

5.2 Combined multi-peril perspective

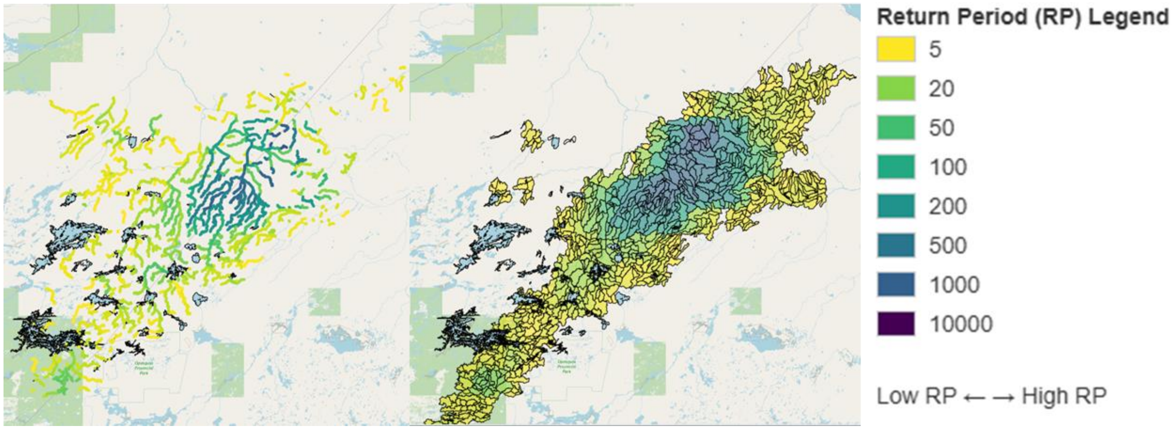

Figure 5: Combined view of fluvial and pluvial event close to Nelson and Severn, event duration is 6 days, max return period of flows is higher than 1 in 1000 years.

Although a full multi-peril analysis is beyond the scope of this paper, the integrated design of the hazard components and the stochastic event catalog enables combined views of fluvial, pluvial and storm surge flooding. In coastal or Great Lakes regions, pluvial flooding driven by intense rainfall can coincide with elevated water levels and overland inundation from storm surge, while widespread storm systems may generate both high river flows inland and pluvial flooding in urban centers. Within the catastrophe modelling framework, such combined situations are represented by single catalog events that carry consistent hazard layers from all relevant components. This allows analyses of compound flooding scenarios and provides a more realistic picture of potential losses for portfolios exposed simultaneously to river, surface water and coastal flooding.

5.3 Methodological strengths and current limitations

The presented examples illustrate several methodological strengths of the Canada Flood Model 3.0. High resolution DEMs and detailed terrain conditioning improve the realism of simulated flow paths and local inundation patterns. The integration of an extensive hydrometric network, frequency analysis and graph-based extrapolation for design flows supports a consistent representation of fluvial hazard across gauged and ungauged catchments. For pluvial, the use of EMDNA, SCDNA to derive spatially consistent IDF curves, combined with design storms constructed using a Chicago type method, allows urban surface water flooding to be represented in a physically meaningful way. The atmospherically driven event catalog, based on long climate simulations and HYPE rainfall–runoff modelling, provides a coherent framework for simulating a broad range of events under current and future climates.

At the same time, several limitations and ongoing developments need to be acknowledged. Calibration and validation against historical flood events and claims data are still in progress and will be documented separately as well as detailed description of entire Vulnerability component framework with unique calculation of loss ratios based on both water depths and velocities. In some regions, especially in sparsely monitored or data poor areas, uncertainties in input datasets and hydrological parameters remain higher. The representation of urban drainage systems is necessarily simplified and may not capture all local infrastructure details. Finally, while the integration of storm surge with pluvial and fluvial components is conceptually implemented, further work is required to fully characterize compound flooding and associated dependencies in a probabilistic way.

Overall, the preliminary results suggest that the methodological choices underlying the Canada Flood Model 3.0 provide a solid basis for detailed, multi-peril flood hazard assessment across Canada, while also indicating where additional data and model refinements can further improve performance.

6 CONCLUSION

This paper presented the methodological framework and architecture of the Impact Forecasting Flood Model for Canada 3.0. The model combines high resolution terrain data, hydrological analysis and 2D hydrodynamic simulations to represent fluvial, pluvial and storm surge flooding across the entire Canadian territory of about 10 million km².

A key element of the approach is the integration of dense hydrometric observations, frequency analysis and graph-based extrapolation of design flows for fluvial hazard, together with IDF based design storms and Chicago type hyetographs for pluvial hazard. These components are driven by long, bias corrected and downscaled climate forcing, transformed into river flows using the HYPE model and organised into an atmospherically driven stochastic event catalog.

Illustrative examples show how the model captures detailed floodplain inundation, urban pluvial flooding and combined fluvial–pluvial impacts, providing a consistent basis for multi-peril flood risk assessment. Ongoing and future work focuses on systematic calibration and validation against observed events and claims data, refinement of urban drainage representation and more detailed treatment of compound flooding, including interactions with storm surge.

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