Flood Hazard Identification and Mapping Program (FHIMP): Research Update

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ABSTRACT

The Government of Canada's Flood Hazard Identification and Mapping Program was established in 2021 to help Canadians better plan and prepare for future flood risks. A key activity of the program is to support the advancement of flood hazard studies through research and developing technical guidance to promote best practices for flood mapping in Canada. In this presentation, Environment and Climate Change Canada will provide updates on the ongoing research activities that were initiated since 2024, including work completed internally as well as by external academic and research institutions. These initiatives aid in decision-making for land use planning, emergency management, and the protection of communities and infrastructure from potential flood damage

KEYWORDS: Hydrological & hydraulic modelling, flood mapping, climate change, machine learning

1 INTRODUCTION

Through the Flood Hazard Identification and Mapping Program (FHIMP), Environment and Climate Change Canada (ECCC) is investing in Canadian universities and research organizations to foster new knowledge and train the next generation of flood experts in Canada. Within the first three years of the program (Phase 1), eleven (11) academics and research organizations were recipients of the Grant and Contribution (G&C) funding program, with fifteen (15) research projects completed. In the second phase (2024-28), which is the focus of this paper, nine (9) projects were funded. The key themes of these projects included hydrological modelling and data, exploring different methodologies for flood estimation, investigating the impacts of bathymetric data on flood mapping, understanding flood mechanisms, and analysing climate change impacts, and estimating future hydrology.

With the various research topics assessed and currently on-going, the objective of this paper is to provide an overview of the activities being completed; the paper does not focus on detailed technical aspects of each individual project.

The sections below present the nine (9) different projects funded by the FHIMP during the second phase of the program.

2 MACHINE LEARNING FOR ENHANCED HYDRODYNAMIC AND FLOOD IMPACT MODELLING IN COLD-REGION RIVERS

2.1 Summary

Flood modeling in cold-region rivers is challenging due to ice processes and the computational cost of high-resolution simulations. This project addresses these issues by developing a hybrid framework that combines physics-based models with machine learning (ML) to deliver accurate, efficient predictions for real-time forecasting and climate scenario analysis. Case studies include the St. Lawrence and Athabasca Rivers.

2.2 Objectives

The project is guided by three main objectives:

- Develop and validate models: Build high- and low-resolution hydrodynamic models with ice processes and create a comprehensive simulation dataset.
- Advance ML techniques: Design physics-informed ML models for surrogate prediction and super-resolution downscaling.
- Operational integration: Embed ML-enhanced models into an automated flood forecasting system linked to hydrologic and climate data.

2.3 Progress to Date

Significant progress has been achieved in model development and machine learning integration. Hydrodynamic modelling has advanced with Delft3D models for both synthetic and real rivers, and high- and low-resolution datasets are being assembled. For ML-based downscaling, initial architectures such as U-Net and encoder–decoder have been tested, while work continues on dynamic, physics-consistent models using graph neural networks (GNN) and Fourier neural operators (FNO). In surrogate modelling, POD–DNN and hybrid RF–ANN models have been developed, and physics-informed neural network (PINN) approaches are currently under development.

2.4 Next Steps

The next phase of the research will focus on completing model development and enabling operational deployment. In the short term, the priority would be to finalize machine learning models, expand datasets, and benchmark hybrid approaches. Over the longer term, efforts will focus on integrating these models into forecasting systems, validating them against real flood events, and adapting the framework for application to other rivers, including data-scarce northern regions.

3 HYDROLOGIC-HYDRAULIC MODELLING FRAMEWORK FOR IMPROVING DYNAMIC ICE JAM FLOOD MAPPING UNDER A CHANGING CLIMATE

3.1 Summary and objective

River ice jams cause significant flood risks in many areas of Canada, but assessing this risk is challenging since the peak water levels during river breakup depend on many factors such as ice jam location, ice strength, river discharge, and dynamic ice jam releases. Existing ice jam flood maps rely on historical records, yet in many regions the data needed for accurate ice jam flood frequency analyses are lacking.

This research project aims to address this challenge by developing an "operations-ready" framework that integrates hydrological, hydraulic, and ice modelling to enhance the characterization of breakup hydrographs. This comprehensive modelling framework will improve both "current generation" and "next generation" ice jam flood maps, especially where historical data is limited. It will also make it possible to consider the effects of climate change, addressing an important source of uncertainty in “current generation” flood maps.

3.2 Progress to date

At this stage of the project, several activities have been completed with others are ongoing. These activities include:

- Compilation and analysis of historical records of ice jam occurrence in the study reach (historical flight records, historical oblique air photos, all remote sensing data).
- Monitoring of the Smoky River 2025 breakup.
- Bank and overbank survey of 6 sites.
- Development of ice consolidation modelling capability in River1D (in progress), and implementation of a quasi-dynamic ice consolidation algorithm to determine where the ice is unstable and where the ice should move to. The algorithm is currently being tested.
- Compilation of climate data.

3.3 Next steps

The next steps in the project have been divided into 4 components:

- Component 1: Gain understanding of breakup on the Smoky River and prepare information for the modelling framework
- Component 2: Improve the River1D ice process model to enhance its ability to simulate ice jam formation locations and ice movements
- Component 3: Integrate the Raven hydrological model and the River1D hydraulic and ice process model
- Component 4: Utilize the modelling framework to generate results

4 INTEGRATING HYDROLOGICAL MODELLING UNCERTAINTY INTO FLOOD CHARACTERIZATION FOR FUTURE CLIMATE

4.1 Summary

The project connects ECCC's Surface Prediction System (SPS) to outputs of the Canadian Regional Climate Model (CRCM). It allows different land-surface models to be run offline at different resolutions from the regional atmospheric model. Land-surface models simulate water runoff and infiltration, which are then routed onto a river network to assess the influence of climate change on hydrologic regimes and floods.

4.2 Objectives

The main goal of the project is to build a physically-based hydrological modelling platform that facilitates the evaluation of the hydroclimatologic impacts of climate change, and in particular flood mechanisms.

4.3 Progress to date

To date, the following modelling tasks have been completed:

- Implemented SPS at Ouranos and ran the land surface model SVS from CRCM's outputs;
- Implemented the CLASS land-surface model within SPS;
- Routed SPS outputs on the southern Québec river network using Raven;
- Identified and implemented hydrological signatures to be used in the evaluation of the performance of the model framework.

4.4 Next steps

Although the modelling work is currently being completed, the research team will also be evaluating the calibration options as well as performance of the models. The datasets produced will be published and accessible to the public.

5 ASSESSMENT OF EMERGING TECHNOLOGIES TO OPTIMIZE ICE-JAM FLOOD RISK ASSESSMENT AND MAPPING

5.1 Summary

This project investigates the dynamics of open-water and ice-jam flooding, which pose serious socio-economic and environmental risks. It leverages advanced remote sensing technologies—the SWOT mission and GNSS-IR—to improve flood hazard mapping and forecasting. SWOT provides high-resolution two-dimensional water surface maps, while GNSS-IR offers non-contact water level measurements. The research applies these tools to rivers in Québec and Alberta, analyzing sensor signals under ice-covered and open-water conditions to retrieve critical hydrological parameters. By integrating these observations into geospatial models, the project aims to enhance flood prediction accuracy and develop next-generation dynamic mapping capabilities, advancing hydrology, hydraulics, and remote sensing.

5.2 Objectives

The main goal in this project is to evaluate the added value of combining GNSS-IR and SWOT and other altimetry data to achieve improved retrieval of hydrological parameters during the ice-on season for supporting ice-related flood monitoring.

5.3 Progress to date

To date, the project team has deployed GNSS-IR sensors and cameras along the Chaudière River, supported by winter-ready power systems, and conducted field campaigns to collect water level and ice data. A processing codebase and machine learning modules were developed for surface-type classification, later enhanced with deep learning and GPU acceleration. Ground truth masks were generated using Sentinel-2 imagery and DEMs, enabling automated river ice detection with SWOT data, though further refinement is needed for complex melt conditions. Preliminary results and methods have been shared at major conferences, generating valuable feedback for improvement.

5.4 Next steps

The remaining tasks to achieve the project objective include:

- Refining and validating performance of the classification methods of GNSS signals.
- Sensor leveling and integration of satellite altimetry.
- Field work to capture a broader range of hydrological and ice-cover conditions.
- Deep learning river ice classification of SWOT data.

6 ESTIMATION OF INTENSITY–DURATION–FREQUENCY (IDF) CURVES FOR PRECIPITATION UNDER CURRENT AND FUTURE CLIMATE CONDITIONS ACROSS CANADA

6.1 Summary and objectives

This project aims to improve the estimation of intensity–duration–frequency (IDF) curves for precipitation across the entire Canadian territory, both under current and future climate conditions. It seeks to make better use of available information by incorporating the Canadian Surface Reanalysis

(CaSR) as well as the dependence between accumulation durations, spatial dependence, and the influence of climate change. Ultimately, the project will produce a unified statistical framework capable of delivering IDF curves at any location in Canada while providing a robust quantification of uncertainty.

More specifically, the project involves:

- Modelling the dependence between accumulation durations to produce more coherent and physically consistent IDF relationships.
- Modelling the spatial dependence using a Bayesian hierarchical model informed by the CaSR reanalysis, ensuring spatial consistency of IDF estimates across Canada.
- Integrating climate change effects into the estimation of IDF curves to reflect both current and future climate conditions.
- Developing a unified statistical model combining duration dependence, spatial dependence, and climate change effects to generate IDF curves with appropriate uncertainty estimates at any location.

6.2 Progress to date

- The dependence between accumulation durations has been successfully modelled, achieving the first objective.
- Climate change effects have been incorporated into the IDF curve estimation framework, completing the third objective.
- Work on the second objective—modeling spatial dependence using a Bayesian hierarchical model and CaSR—is underway.

Early results demonstrate that incorporating duration dependence and climate change effects leads to improved consistency and realism in IDF curve estimates.

6.3 Next steps

The remaining work on the project is as follow:

- Complete the spatial dependence modelling using the Bayesian hierarchical framework and CaSR data.
- Begin development of the overarching integrated statistical model that will bring together all components—duration dependence, spatial dependence, and climate change effects.
- Ensure that the final framework can produce IDF curves at any location in Canada while providing reliable uncertainty quantification.

7 INTEGRATED FRAMEWORK FOR ASSESSING COMPOUND COASTAL AND INLAND FLOODING UNDER CLIMATE CHANGE ACROSS CANADA

7.1 Summary and objectives

The project develops an integrated statistical, hydrologic, and numerical modelling framework to assess compound coastal and inland flooding across Canada under climate change. Objectives include characterizing multivariate flood drivers, projecting changes in compound pluvial, riverine, and coastal events, and generating flood maps for key regions using advanced models and machine-learning tools.

7.2 Progress to date

- Completed projected analyses of compound pluvial-coastal events over the Pacific, including future storm surge-wave interdependencies.
- Completed numerical modelling for Tofino, including hydrodynamic setup and development of a machine-learning surrogate model for pluvial-surge-tide conditions.

- Analyzed rain-on-snow, saturation-excess, and successive rainfall flooding across North America and regionally over the Great Lakes under climate change.
- Started initial multivariate dependence analyses for key atmospheric, marine, and hydrologic drivers.

7.3 Next steps

- Finalize Raven model calibration for the Atlantic.
- Assess compound riverine-pluvial-coastal flooding for the Atlantic region.
- Evaluate future compound pluvial-coastal events across the Atlantic, Pacific, and Great Lakes.
- Extend numerical and hydrologic modelling to additional coastal sites.
- Finalize and apply the machine-learning surrogate model for large-ensemble compound flood simulations.

8 DEVELOPING A CONSOLIDATED FLOOD FREQUENCY ANALYSIS SYSTEM FOR CANADA IN A CHANGING CLIMATE

8.1 Summary

Researchers will implement comprehensive hydrometeorological and statistical modelling processes required for modelling the hydrologic impacts of climate change throughout Canada. The modelling framework will help increase the understanding of future flood hazards for the purpose of improving floodplain mapping methods and standards. The purpose of the framework is to support more informed decision-making and policy development, while also serving as an essential tool for sharing knowledge between researchers and flood mapping practitioners.

8.2 Objectives

The primary objective of the work is to develop a consistent hydrometeorological and statistical modelling chain to span Canada. Specifically, the two goals are:

- To develop hydrological models to predict how flooding will be affected by climate change across Canada.
- To create a method for flood frequency analysis that accounts for changes in flood magnitudes and types on rivers in Canada between the present day and the end of the century (2100).

8.3 Progress to date

In part 1 of the project, the research team is currently conducting hydrologic modelling for gauged and ungauged areas across Canada. They are developing a national hydrological prediction system using downscaled climate scenarios to estimate flows at all floodplain endpoints. This system is being built on the model-agnostic framework from the Global Water Futures (GWF) program. Researchers are running ensembles of models (HYPE, MESH, SUMMA) across selected basins under current climate conditions to evaluate parameterization, model accuracy, and suitability for climate change impact studies.

The second part of the project is applying climate scenarios for floodplain mapping and uncertainty analysis. A key focus is identifying the best methods for determining streamflow values for floodplain delineation that accounts for climate change. Traditional flood frequency analysis (FFA) assumes floods follow a single distribution, which may not hold when multiple mechanisms (snowmelt, rainfall, rain-on-snow) drive flooding. Mixed distributions can address this but require splitting flood records by type, increasing uncertainty. Peaks-over-threshold (POT) methods improve estimates but involve subjective choices and assumptions. Flood type identification often relies on seasonality or conditions during the event. This work intends to improve FFA realism by using novel Metastatistical approaches that incorporate both extreme and ordinary events to better represent physical flood-generating processes.

9 CLIMATE CHANGE AND HURRICANE IMPACTS TO ATLANTIC COASTS

9.1 Summary

This project applies a suite of coastal numerical models to assess storm-driven inundation in vulnerable Atlantic Canada sites. The approach combines a regional Delft3D–SWAN hydrodynamic-wave model for Nova Scotia's coast, high-resolution site modelling, and XBeach morphodynamic simulations for overwash and flooding. Martinique Beach serves as the key study site, where field observations include waves, water levels, groundwater, and beach topography. Validated models will be used to evaluate future climate scenarios, including sea-level rise and changing storm characteristics, producing detailed coastal floodplain maps and a transferable methodology for hazard assessment across Canada.

9.2 Objectives

The goal of the proposed research is to strengthen floodplain modelling and mapping science and practice through the development and application of coastal numerical models for extreme storm events. Validated by field observations collected at an exposed ocean beach to measure model performance, the models will be used to simulate the inundation of shorelines on ocean coasts caused by the interaction of surface waves, storm surges, and tides that drive flooding and erosion

9.3 Progress to date

The Scotian Shelf model has been completed and applied to simulate hurricane-driven waves. Field sensors were deployed at Martinique Beach in 2025, with data collected on waves, groundwater, and beach topography. Two major storms caused significant erosion and morphological changes, and all data is now archived and under analysis. Preliminary results have been obtained and presented at a national conference in June 2025.

9.4 Next steps

The reserach team will finalize the fine-scale XBeach model for Martinique Beach using field data for validation and apply it to simulate wave runup and inundation. After analyzing the 2025 data, a second field season will be planned for 2026 to continue monitoring hurricane impacts, with possible adjustments to instrument locations. The first journal manuscript on regional wave modeling will be submitted in 2026, and additional theses and publications are scheduled through 2028.

10 PROBABILISTIC PREDICTIONS OF HYDROLOGICAL EXTREMES ACROSS TIMESCALES AND THEIR INFORMATION-THEORETICAL EVALUATION

10.1 Summary and objective

This project is investigating methods to advance probabilistic extreme flood predictions across timescales for both gauged and ungauged basins, using machine-learning models. A framework for Information-theoretical evaluation of such forecasts will be developed to properly measure forecast quality of the predictive distributions. The expected results are prediction models producing probabilistic flow predictions for approximately 100 locations located mainly in British Columbia and Yukon, which, on average, will show increased reliability of forecasted tail probabilities of extremes compared to benchmark models.

The reliability will be demonstrated through an information-theoretical evaluation framework that will be developed alongside the modeling. This evaluation framework will, for example, use metrics that directly work on forecast distributions, such as Entropy and Kullback-Leibler divergence.

More specifically, the project aims at applying machine-learning (ML) methods to improve the estimation of probabilities of extreme flows in BC and the YT. It will also assess the ability of these ML methods to accurately estimate the probabilities of extreme flow occurrences, both at gauged and ungauged sites, and for different timescales (from short lead-time forecasts up to long-term exceedance probabilities).

10.2 Progress to date

Progress so far has focused on laying the groundwork for probabilistic flood prediction using machine-learning models. Most of the key predictors and evaluation metrics for estimating flow probabilities have been identified. Three major families of methods for estimating daily flow probability density functions (PDFs) at ungauged sites have been tested across more than 700 basins in the Pacific Northwest, showing comparable performance individually but notable improvements when combined. Preliminary experiments have explored training LSTM-based models using information-theoretical metrics, and the Kullback–Leibler divergence has proven to be a robust measure for assessing PDF accuracy, even under varying flow units and intermittent conditions, provided measurement uncertainty is explicitly accounted for.

10.3 Next steps

- Continue to assess different methods to directly output encodings of full distributions.
- Adapt the previous methodologies to fully ungauged sites.
- Adapt the methodology for large-scale, longer timescales, non-stationary flood frequency analysis.
- Compare previous methods to conventional static methods based on observed flows.
- Adapt the previous methodology to ungauged sites.
- Perform the predictions and estimated non-stationary flood-frequency analyses for ungauged sites and present them in an experimental system.

11 CONCLUSION

Investment in research by the Government of Canada through the Flood Hazard Identification and Mapping Program continues to advance the science of flood mapping in Canada. Outcomes of the research will help practitioners better assess flood hazard under a changing climate.