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Towards a coherent flood forecasting framework for Canada: Local to global implications

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Abstract

Operational flood forecasting in Canada is a provincial responsibility that is carried out by several entities across the country. However, the increasing costs and impacts of floods require better and nationally coordinated flood prediction systems. A more coherent flood forecasting framework for Canada can enable implementing advanced prediction capabilities across the different entities with responsibility for flood forecasting. Recently, the Canadian meteorological and hydrological services were tasked to develop a national flow guidance system. Alongside this initiative, the Global Water Futures program has been advancing cold regions process understanding, hydrological modeling, and forecasting. A community of practice was established for industry, academia, and decision-makers to share viewpoints on hydrological challenges. Taken together, these initiatives are paving the way towards a national flood forecasting framework. In this article, forecasting challenges are identified (with a focus on cold regions), and recommendations are made to promote the creation of this framework. These include the need for cooperation, well-defined governance, and better knowledge mobilization. Opportunities and challenges posed by the increasing data availability globally are also highlighted. Advances in each of these areas are positioning Canada as a major contributor to the international operational flood forecasting landscape. This

Louise Arnal and Alain C. Pietroniro are co-first authors.

article highlights a route towards the deployment of capacities across large geographical domains.

KEYWORDS

Canada, cold regions, flood, forecasting, hydrology

1 | INTRODUCTION

Hydrologically, Canada is one of the most diverse countries in the world with its large landmass, complex, and wide-ranging hydrological regimes and extensive river system covering 15 major terrestrial ecozones (Government of Canada, 2020). This complexity is underlain by cold regions processes that dominate the terrestrial component of the hydrological cycle. Floods in Canada have historically been caused by snowmelt, ice jams, and heavy rainfall (Burn et al., 2016; Buttle et al., 2016; Pietroniro et al., 2004; Rokaya et al., 2018). Flash flooding in provinces like Nova Scotia, or parts of southern Ontario can be contrasted with large flooding events like the Red River flood in Manitoba in 1997, where flood preparations are made days in advance. Flooding is estimated to be Canada's costliest natural disaster; the last two decades have seen unprecedented flood events and related damage costs across Canada (Stadnyk & Déry, 2021). The recent November 2021 catastrophic flood event that hit British Columbia was one of the costliest natural disasters in Canada, particularly when the impacts on agriculture, transportation, and losses to gross domestic product are considered (Judd, 2021).

These hydroclimatic differences notwithstanding, the overall challenges of flood forecasting in Canada are similar to flood forecasting challenges over other large spatial domains (e.g., Europe, as opposed to individual European countries). While the meteorological forecast inputs often dominate the flood forecast uncertainty as the lead time increases (Jha et al., 2018; Wu et al., 2020), this depends on the characteristics and location of the flood event. Several factors additionally affect the nonlinearity between precipitation anomalies and flood hazard, including land surface and subsurface memory (e.g., snowpack and groundwater storage), the topology of the river network, the catchment concentration time, and anthropogenic regulation (e.g., reservoirs; Stephens et al., 2015).

The scientific and computational advances accumulated over the last few decades have made large-domain flood forecasting possible. Existing operational large-domain fluvial flood forecasting systems (summarized in Table 1) aim to provide flood early warnings by running a hydrological model into the future, forced with a deterministic or an ensemble of meteorological forecasts (e.g., from a Numerical Weather Prediction [NWP] model) to produce deterministic or probabilistic predictions of streamflow (Figure 1). In recent decades, flood forecasting has shifted from deterministic to probabilistic forecasting in a first attempt to characterize the irreducible uncertainties in meteorological forecasts and hydrological models. This transition has brought with it the potential to provide earlier awareness of the risk of extreme events, such as floods (Wu et al., 2020). At the forefront of this transition since 2004 is the international Hydrologic Ensemble Prediction Experiment (HEPEX) community (https://hepex.inrae.fr; Schaake et al., 2007). Most operational large-domain fluvial flood forecasting systems presented in Table 1 are centered around one or multiple hydrological models. The suitability of these models for flood forecasting depends on process representation, flexibility in spatial and temporal resolutions, input data requirements, code availability, and computational costs of implementation and maintenance, among other factors (Kauffeldt et al., 2016).

Canada is the only G7 country without a national flood forecasting or flow guidance system. The working distinction between flow guidance and flood forecasting in Canada lies in the level of responsibility and decision-making, with flood forecasters having responsibility for producing the official forecasts and any subsequent emergency management decisions. Flood forecasting in Canada is largely considered a provincial responsibility and is carried out to varying technical levels by many of the 13 provincial and territorial governments and various municipalities across the country, and some of the 99 Ontario conservation authorities (Zahmatkesh et al., 2019). The benefit of this fragmented approach is that the bespoke operational modeling and forecasting systems are specifically tailored to work at regional scales and to tackle unique local hydrological challenges. The main disadvantages of this incoherence are the dispersion of capacity, lack of integration with weather forecasting, inconsistent resource levels, and the duplication of forecasting services on transboundary river basins. Indeed, recent flood events have challenged local capabilities to forecast and prepare for large floods. Coherence translates into a flood forecasting framework which is

TABLE 1 Large-domain operational flood forecasting systems.

	EFAS (European Flood Awareness System)	GloFAS (Global Flood Awareness System)	HYPE (Hydrological Predictions for the Environment)	FFWS (Flood Forecasting and Warning Service)
Domain	Europe	Global	Global, Europe, Arctic	Australia
Institute	Part of the Copernicus Emergency Management Service (CEMS), developed by the European Commission's Joint Research Centre (JRC) and operated by an EFAS consortium	Part of the CEMS, developed by the JRC and the European Centre for Medium-Range Weather Forecasts (ECMWF)	Swedish Meteorological and Hydrological Institute (SMHI)	Bureau of Meteorology (BoM)
Method overview	Lisflood distributed hydrological rainfall-runoff model, driven by NWP deterministic and ensemble products	Lisflood distributed hydrological rainfall-runoff model, driven by NWP ensemble product	HYPE distributed rainfall-runoff model, driven by NWP deterministic product	GR4H lumped rainfall-runoff model, driven by NWP deterministic and ensemble products
Lead time	15 days; sub-seasonal to seasonal outlooks also available	30 days; seasonal outlook also available	10 days; seasonal and climate outlooks also available	7 days; seasonal outlook also available
Flood Warning Dissemination	Formal flood notification issued to EFAS partners, Emergency Response Coordination Centre and the Civil Protection	Complements national and regional services and supports international organizations in flood anticipation activities	Used operationally in the SMHI flood warning service for Sweden	Warning service for Australia
Website	https://www.efas.eu	https://www.globalfloods.eu	https://hypeweb.smhi.se	http://www.bom.gov.au/water/floods
Literature	Smith et al. (2016)	Alfieri et al. (2013); Harrigan et al. (2023)	Andersson et al. (2017); Arheimer et al. (2020); Donnelly et al. (2015)	Kabir et al. (2018)

HEFS (Hydrologic Ensemble Forecast Service)	GLOFFIS (Global Flood Forecasting and Information System)	OpenForecast	CNFFS (China National Flood Forecasting System)
US	Global	Russia	China
National Oceanic and Atmospheric Association (NOAA)'s National Weather Service	Deltares	Roshydromet	Ministry of Water Resources, Bureau of Hydrology
Suite of hydrological models, driven by NWP deterministic and ensemble products	Suite of wflow models, driven by NWP ensemble product	GR4J and HBV, driven by NWP ensemble product	Suite of hydrological models, driven by NWP ensemble products
7 days; seasonal outlook also available	14 days	7 days	2 days
Warning service for the US	Provides early awareness where local warning services are not available	Early warning for gauges across Russia	Used in 33 flood forecast centers at national, river-basin, and provincial levels in support of flood management throughout the country

(Continues)

TABLE 1 (Continued)

HEFS (Hydrologic Ensemble Forecast Service)	GLOFFIS (Global Flood Forecasting and Information System)	OpenForecast	CNFFS (China National Flood Forecasting System)
https://water.weather.gov/ahps/forecasts.php	https://blueearthdata.org/wl	https://openforecast.github.io	Not available
Demargne et al. (2014)	Werner et al. (2013)	Ayzel (2021); Ayzel et al. (2019)	Guo et al. (2004); Liu (2020); Zhang and Liu (2006)

Note: Update of the overview provided in Emerton et al. (2016), using recent literature. More information about each system can be found in the accompanying literature.

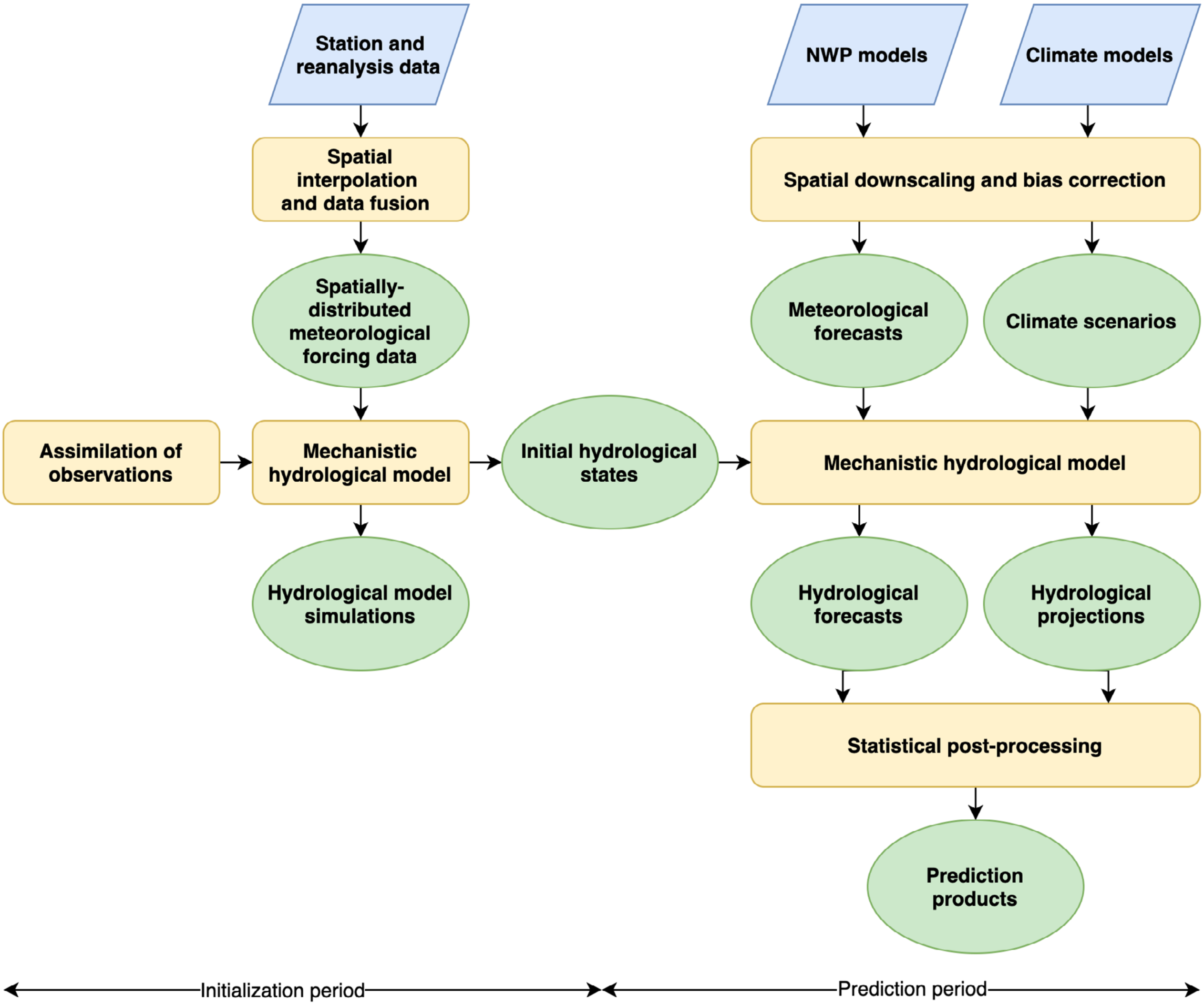

FIGURE 1 Key components of hydrological prediction systems. The blue parallelograms define inputs, the yellow boxes define methods and models, and the green circles define model outputs.

consistent amongst the different authorities, allows proactive communication, and open data sharing.

The need to modernize flood forecasting systems is a particularly acute issue as climate change is altering rainfall and snowfall patterns, leading to increased temperatures, and impacting snow and ice melt, river ice breakup and frozen ground thawing. As a result, the frequency of water-related natural hazards is increasing around the world

(Jiménez Cisneros et al., 2014; UNESCO, 2020), and particularly in high-latitude regions such as Canada. Concerns about the costs of future floods have motivated a change in approach to forecasting. Canada is advancing the development of a nationally consistent flow guidance system that accounts for both the constitutional and hydrological realities of the country and would support nation-wide flood risk management and disaster risk reduction in a climate change context.

In 2018, the Meteorological Service of Canada (MSC) and the National Hydrological Service (NHS) began developing a national flow guidance system for Canada in consultation with provincial and territorial partners (see Appendix A for a glossary of Canada-specific acronyms). In tandem with these efforts, the Global Water Futures program (GWF) has been conducting research to advance the scientific underpinnings of hydrological modeling and forecasting. Since 2016, scientists in GWF have also engaged in national discussions to promote the benefits of a nationally coordinated flood prediction system. As part of this process, GWF and the NHS have co-hosted two Canadian flood forecasting workshops/forums (2019, 2021), with the aim to develop a community of practice to encourage shared experiences and knowledge amongst the different entities that are responsible for flood forecasting. Initial discussions have already provided tremendous insights into the various local and national viewpoints, and methods to address Canadian hydrological needs and challenges.

This article provides a Canadian perspective on operational flood forecasting, situating it within the global context. Section 2 briefly describes the current regional approaches to flood forecasting within Canada. Section 3 highlights ongoing national operational water modeling and forecasting efforts, and research advances that are making their way into a more coherent national flood forecasting framework for Canada. Finally, Section 4 discusses future directions for flood forecasting in Canada and globally. It underlines how Canada, as a late adopter, can benefit from global flood forecasting advances (in terms of global hydrological systems, international expertise, and scientific developments), and how it contributes expertise in various domains to the rest of the world.

2 | CURRENT FLOOD FORECASTING PRACTICE ACROSS CANADA

2.1 | Canadian flood forecasting challenges

Canada's river basins span nearly 10 million km^2, flowing to the Atlantic, Pacific, and Arctic Oceans, and store the largest proportion of freshwater resources in the world. Canada is divided hydrologically into several major drainage areas as summarized by Stadnyk and Déry (2021; Figure 2). Unlike other (typically smaller) jurisdictions with relatively homogenous flood forecasting needs, Canadian hydrological processes vary widely, creating a diversity of flood generation processes across the country (Burn et al., 2016). Complicating this diversity further is the non-uniform and substantial impact that climate

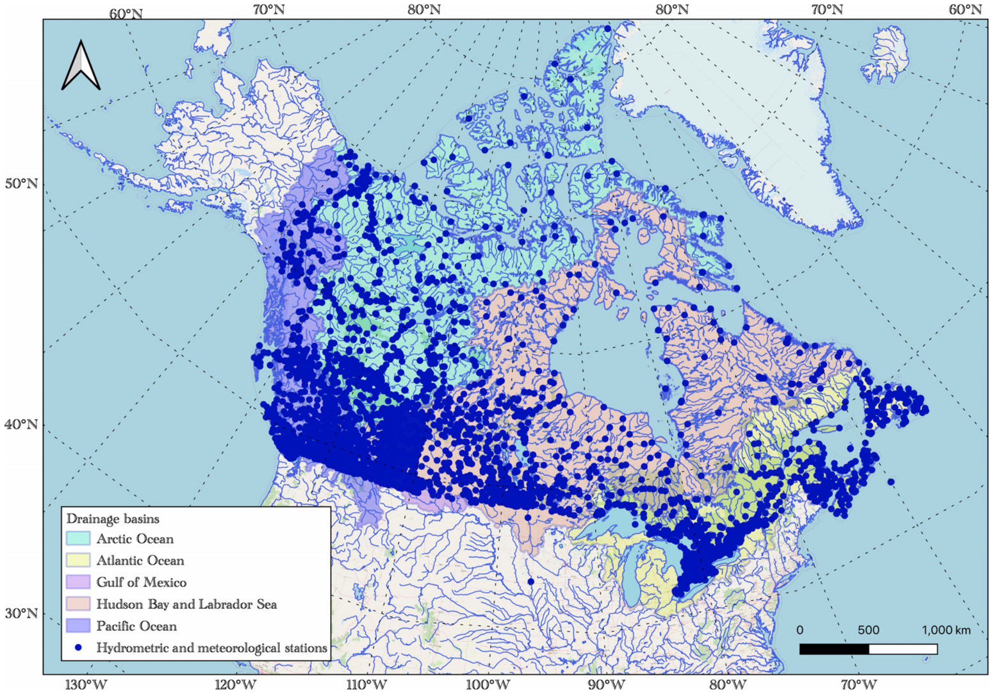

FIGURE 2 Map of the 2500 active hydrometric and 1800 active meteorological stations that provide near real time data across Canada. The main drainage basins in Canada are shown in different colors (shapefile from the Water Survey of Canada [WSC]).

change is imposing on flood frequency, extent, and duration (Burn & Whitfield, 2015; Hodgkins et al., 2017).

Several studies have classified the complex flooding landscape across Canada into distinct regimes. Burn et al. (2016) classify flood behavior in Canada into three major flood generation regimes: rainfall-driven, snowmelt-driven and mixed. They use this classification system to highlight the large but declining magnitude of snowmelt-driven events, the increasing importance of rain-on-snow and rainfall-driven flood events, and an overall increase in the occurrence of flooding in Canada. Similarly, from an analysis over a 30-year observation period from 1974 to 2003, Cunderlik and Ouarda (2009) report the decreasing importance of spring snowmelt flood events across Canada, as well as the increasing relevance of late fall (rainy season) events for determining antecedent moisture conditions as a major determinant of flooding in the spring. Musselman et al. (2018) describe the changing nature of rain-on-snow events across western North America. These processes have important scaling considerations. Snowmelt, lake effect, orographic and frontal storms have large spatial and temporal extents and can impact large river basins. Convective rainstorms have high precipitation intensities and can cause severe flooding due to overland flow at smaller scales (Buttle et al., 2016).

Buttle et al. (2016) emphasize the need for more reliable historical flood records in Canada to understand the temporal changes in flood-generating mechanisms at a national level. A specific example of changing flood regimes in Canada includes the contrast between the 2011 and 2014 Assiniboine River floods in Saskatchewan and Manitoba (Prairie region; Ahmari et al., 2015; Blais et al., 2015). The 2011 flood was caused by high antecedent moisture conditions in the fall of 2010 (150%–200% of normal precipitation), followed by high snowpack accumulation across the basin (90%–130% of normal), and by a very wet spring (>350% of normal precipitation). This resulted in peak flows that lasted more than 120 days. This event was presented as a snowmelt-driven spring flood event both in terms of the timing of peak flow and causation (higher than normal snowpack on top of already wet antecedent conditions; Blais et al., 2015). The processes that led to this extreme event are typical for the prairies. In contrast, the 2014 Assiniboine River flood was the first-ever pluvial flood event in 130 years of record in this area. It was caused by heavy rains occurring on an already saturated basin, with June and July peak flows dwarfing the spring freshet flows (Ahmari et al., 2015). Some basins recorded their all-time high flows in a period when they are normally dry (Dumanski et al., 2015). This event was unprecedented for the prairies, where rainfall resulted in severe and sustained flooding and was responsible for the annual maximum peak flow. The contrast between both flood events exemplifies a more general shift in climate drivers across Canada over the last decades.

River ice jams (that occur due to accumulating ice blocking the downstream flow of ice and water) and subsequent backwater flooding are another important challenge in Canada. Ice-jam floods are more common during the ice cover breakup period in spring, but they can also occasionally occur during river freeze-up in fall or during mid-winter breakups. Ice jams can result in high water levels that can be many meters above summer floods for equivalent or lower discharges (or river flows), due to the ice jams' large aggregate thickness and underside roughness (i.e., the ice-water interface; Beltaos, 2014). Furthermore, a range of ice jam induced backwater levels are possible for a given discharge, which makes an ice-jam flood difficult to predict (Lindenschmidt & Rokaya, 2019). Previous studies (e.g., Burrell et al., 1990) have shown that damages from ice-jam floods often surpasses that of ice-free floods—for example, the 2020 ice-jam flood in Fort McMurray in western Canada caused more than a billion Canadian dollars in damages (Nafziger et al., 2021).

Forecasting ice-jam floods is challenging since it involves flow forecasting, as well as an understanding and the modeling of complex and non-linear processes of river ice formation, breakup and ice jamming, and their effect on water levels (Lindenschmidt et al., 2019). Several methods have been introduced in the literature, from simple statistical models (e.g., Mahabir et al., 2006; Tuthill et al., 1996) to more complex machine learning methods (e.g., Sun & Trevor, 2018; Wang et al., 2010) and process-based modeling approaches (e.g., Beltaos et al., 2012; Lees et al., 2021; Lindenschmidt et al., 2019). See White (2003) and Rokaya et al. (2020) for a review of existing methods. It is important to note that existing research developments have not yet fully translated into operational practice and most provinces and territories in Canada do not have an operational ice-jam flood forecasting system (Pietroniro et al., 2021). However, a fully automated operational ice-jam flood forecasting system has been developed for the lower Churchill River in the province of Newfoundland and Labrador and the lower Nelson River in Manitoba (Hudson Bay & Labrador Sea drainage basin on Figure 2; see Section 3.5). Enhanced monitoring of river ice, for example using remote sensing data or flight observations, remains a key component of identifying ice-jam flood risk and communicating early warnings for floods (de Roda Husman et al., 2021).

Added to these diverse flood-generating mechanisms, Canadian rivers have varying amounts of anthropogenic regulation that disrupt the direct rainfall or snowmelt to runoff translation. Based on the definition provided by

Grill et al. (2015), >70% of the Nelson-Churchill River basin (Hudson Bay and Labrador Sea drainage basin) is considered regulated, with >47% being intensely regulated. Notable regulation also occurs in Canada's Arctic draining Mackenzie River basin (up to 19%), and in 74% of the Missouri/Milk-St. Mary's River basins (Gulf of Mexico drainage basin; Stadnyk & Déry, 2021).

2.2 | Flood forecasting responsibilities at the national and provincial/territorial levels in Canada

In contrast to countries with unified flood forecasting systems, the procedures and approaches to flood forecasting in Canada are managed by the 13 provinces and territories, and various municipalities and conservation authorities across the country. These entities operate independently with minimal coordination. There are additionally large differences between jurisdictions in terms of capacity, expertise, available time, priorities, roles, and responsibilities, as well as institutional differences. As a result, the various flood forecasting entities across Canada (referred to as river forecast centers thereafter) have adapted by developing their own unique approaches to data collection, ingestion, and subsequent flood forecasting and early warning systems. Some provinces and territories have year-round river forecast centers with dedicated staff. For example, British Columbia, Alberta, Newfoundland, New Brunswick, and Québec have dedicated River Forecast Centres and staff with many years of experience. Ontario, at the provincial level, has a Flood Forecast and Warning Program, and Saskatchewan has the Water Security Agency. On the other hand, some jurisdictions have much smaller teams and resources, and only offer flood forecasting on a seasonal basis and/or for a small number of river systems (Pietroniro et al., 2021). A map of river forecast centers' locations and a list of their responsibilities are provided in Zahmatkesh et al. (2019); additional information is provided by the Government of Canada (2014).

The mandate of river forecast centers across Canada is to generate potential flood scenarios for river flows and lake levels, and to issue advanced alerts or warnings as needed to protect public safety. During a flood, they work with the local and national emergency government operations centers to advise on conditions and potential needs for actions, including sandbagging and evacuations. Depending on the magnitude or scope of the potential flood, various local agencies including municipal staff or police, or national support such as the Canadian Forces, are called on by the provincial and national authorities to act. The provincial/territorial flood forecasters play a pivotal role in advising governments and decision-makers on the scope, magnitude, and timing of the flood to mobilize a coordinated response.

Forecasts are generally produced on a daily to hourly basis, depending on the issuing agency, the nature of the basin and the modeling approach. Monitoring activities to support forecasting initiatives are commonly integrated within the river forecast centers' mandates; however, forecasters often rely on other monitoring activities at the community, municipal, provincial/territorial, and federal levels. This adds significant complexity when obtaining all relevant data for issuing a reliable forecast. Therefore, most entities invest in generating their own local data management system for their region of interest (Zahmatkesh et al., 2019).

Environment and Climate Change Canada (ECCC) is the national authority responsible for hydrological and meteorological data collection, interpretation, and dissemination. Within ECCC, the National Hydrological Service (NHS), the Water Survey of Canada (WSC), and the Meteorological Service of Canada (MSC) are responsible for hydrological and meteorological data. The WSC operates over 2500 active hydrometric stations in a national cost-shared partnership program with provinces, territories, and other agencies (Government of Canada, 2021b). Water quantity reported as volumetric flow rates and water levels are of primary interest for flood forecasting. The MSC operates over 1800 active meteorological stations, also in partnership with other provincial, territorial and federal partners, and private groups such as Nav Canada. Near Real Time (NRT) and historic data are made publicly available by ECCC via standardized formats that can be readily ingested by operational users. The active hydrometric and meteorological stations providing NRT data at the time of writing are shown on Figure 2. It is important to note that although the figure appears to show a reasonable density of observations, only about 12% of the Canadian terrestrial area is covered by hydrometric networks that meet the World Meteorological Organization (2008) minimum network density standards, most of which are situated south of 55°N (Coulibaly et al., 2013).

Moreover, accurate data measurement in cold regions such as Canada is challenging due to measurement difficulties and uncertainties, and logistics. Ice, sediment, and other effects at river gauge locations require frequent adjustment by hydrometric technicians; such dynamic changes increase uncertainty (Hicks et al., 1995; Rainville et al., 2016). In addition, surface precipitation, a key variable in flood forecasting, is difficult to measure accurately due to high spatial variability that a gauging network may miss, and persistent undercatch in rain (and especially snow) observations (Mekis et al., 2018). Snow water equivalent and snow depth are challenging to measure at the scale needed for operational use, although efforts are made to consolidate data for analysis (Clark et al., 2011; Vionnet et al., 2021). Despite these challenges, observational networks are managed across Canada with consistent procedures to maintain data quality and reliability (Rainville et al., 2016).

2.3 | Canadian provincial/territorial flood forecasting systems

River forecast centers across Canada are now advancing their operational systems through improved data integration, modeling, and community tool development. Zahmatkesh et al. (2019) highlight the responsibilities, unique approaches, and challenges for river forecast centers. Advances in data provision, modeling frameworks, and system developments continuously occur to address some of the technical challenges. However, the underlying institutional separation in these river forecast centers still results in the duplication of efforts and limited sharing of resources and techniques, while challenges in measurement and modeling persist.

All Canadian river forecast centers do not have equal mandates and capacity to perform modeling and model development (see Section 2.2). This results in considerable variability in the quality and breadth of forecasting activities nationally. A range of flood forecasting modeling frameworks have been employed and recently implemented, including Raven, HYDROTEL, WATFLOOD, CLEVER, and MESH (Craig et al., 2020; Fortin et al., 2005; Kouwen, 1988; Luo, 2015; Pietroniro et al., 2007). Hydraulic models tend to rely on the Hydraulic Engineering Center (HEC) suite of models. Legacy models such as the Stream Synthesis and Reservoir Regulation (SSARR) model are still in operational practice but are being phased out due to issues of maintainability. The river forecast centers often complement models with in-house developed rules and regression tools that are trusted and have proven valuable in the past in operational practice.

The most recent advances in Canadian forecasting capacity have come with the introduction of the Delft Flood Early Warning System (Delft-FEWS; Werner et al., 2013), used by many forecasting centers internationally. Delft-FEWS is an open data handling model-agnostic platform developed for flood forecasting and early warning systems. It is a collection of modules designed to manage the forecasting process, and is used by Alberta, Saskatchewan, Manitoba, Québec, and New Brunswick's river forecast centers, along with key utility providers BC Hydro, Manitoba Hydro, and Ontario Power Generation (see sample dashboard on Figure 3). Territorial governments in the Yukon and Northwest Territories are developing Delft-FEWS prototype systems using MESH and Raven modeling frameworks respectively. The adoption of a common platform has enabled shared development, notably improved integration of modeling frameworks such as Raven, HYDROTEL, WATFLOOD, and MESH. Delft-FEWS has also enabled the operational use of Canadian Space Agency RADARSAT Constellation Mission and European Space Agency Sentinel 1 and 2 data for river ice monitoring, a project initiated by the provinces Alberta and Québec (de Roda Husman et al., 2021). This convergence of technology and methods is encouraging and is leading to a national (not federal) approach to flood forecasting and the development of a community of practice in Canada.

At the time of writing, a few provinces/territories use ensemble forecasts for guidance only (i.e., not operationally). At the 2021 Canadian flood forecasting forum, several provinces and territories showed a strong interest to use ensemble methods, but current challenges in their operational implementation are linked with the reliability and availability of ensembles, the dissemination of probabilistic information and resources limitations.

3 | TOWARDS A NATIONAL FLOOD FORECASTING APPROACH FOR CANADA

Flood forecasting in Canada follows a governance model that has matured and developed historically, with local municipal and provincial/territorial forecasting requirements developed to meet local needs. Each province/territory has taken a slightly different approach to how it manages its forecasting requirements, data collection and archiving, and the technologies used. This fragmented approach can lead to slow adoption of new technology and methods and lacks technical coordination with federal agencies. The disjointed efforts across different forecasting entities can be problematic in transboundary basins since the individual systems are not necessarily compatible. However, there are formal and informal mechanisms in place to ensure cooperation and exchange between agencies in shared basins, with governance structures such as the International Joint Commission proving to be highly effective. Despite this coordination and cooperation, there is still a desire for common modeling frameworks, common approaches, and coordinated ensemble forecasting systems (Pietroniro et al., 2021). Moving forward, the plans for the new Canada Water Agency include integrating federal, provincial, territorial, Indigenous, and municipal responses to flooding,

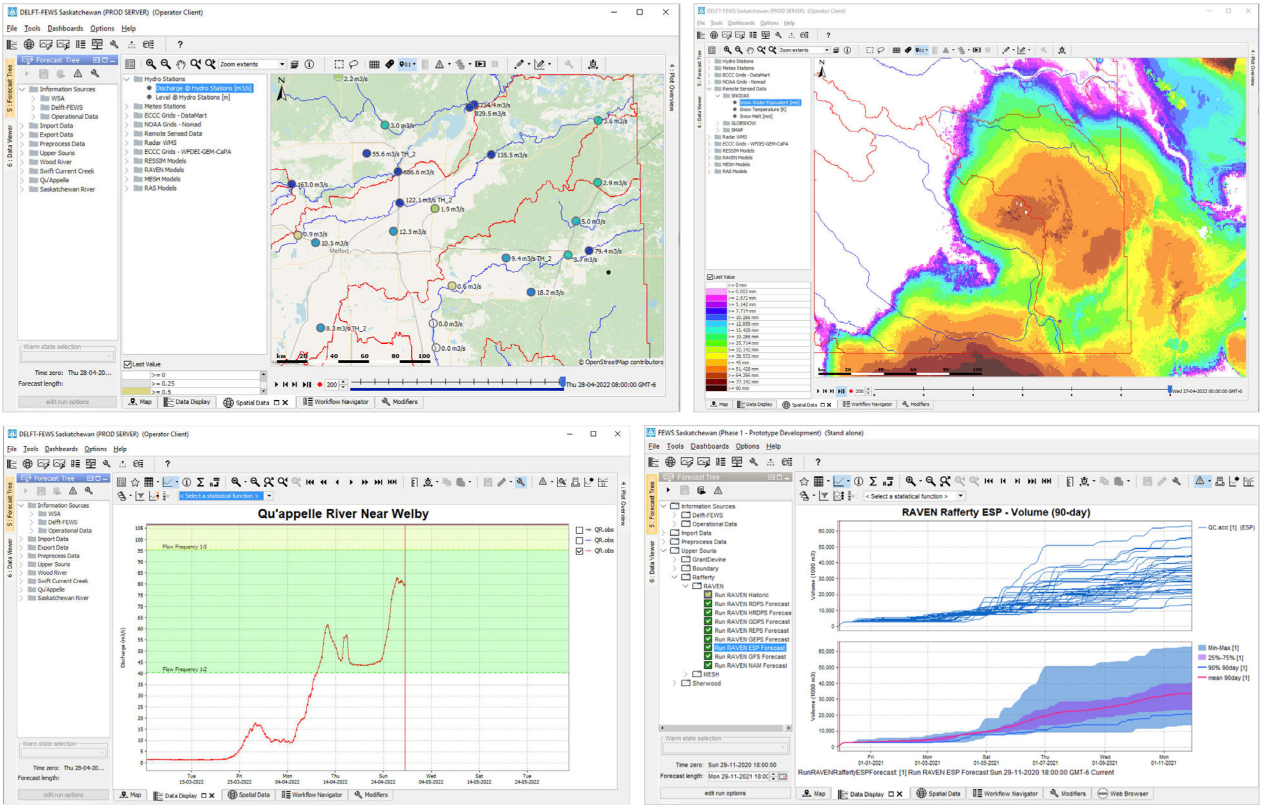

FIGURE 3 Sample dashboard of a Delft-FEWS system, as implemented by the Water Security Agency of Saskatchewan, showing a map of hydrological stations and their discharge (top left panel), a map of snow water equivalent (top right panel), a timeseries of observed discharge (bottom left panel), and a timeseries (top: spaghetti plot, bottom: fan chart) of 90-day volume forecasts (bottom right panel).

which will help support regional flood forecasting (Clark et al., 2023; Government of Canada, 2021a).

3.1 | A new federal approach to flow guidance in Canada

As part of a major reinvestment in modernizing the NHS in Canada, a flow guidance program was formalized. Scientists in Research, Development, and Operations at ECCC's Canadian Meteorological Centre (CMC) constructed the National Surface and River Prediction System (NSRPS; Durnford, Carrera, et al., 2021), which was implemented in CMC's Operations in 2019 with experimental status. Its latest update at the time of writing was implemented on December 1, 2021. The aim of this system is to provide a suite of physically coherent hydrometeorological products at the national level that can inform clients (mostly the provinces and territories) and the wider hydrological community of the current and predicted state of the surface and the availability of water. In addition to providing information for flood prediction, the NSRPS provides information for a range of applications (e.g., for agriculture, forest fire prediction, the prediction of populations of disease-carrying ticks and mosquitoes, and navigation). The NSRPS does not publicly disseminate river flow forecasts, as predicting floods is the jurisdiction of provinces and territories.

An overview of the NSRPS system is shown on Figure 4 and summarized in the sections below (for a more detailed description of the system see Durnford, Carrera, et al. [2021]). This modular system includes three components (hydrometeorological analyses, deterministic and ensemble predictions) for a range of hydrometeorological products on the national grid (i.e., Canada, excluding the Canadian Arctic Archipelago, plus approximately one-third of the United States) at a 2.5 and 1 km resolution.

3.1.1 | Hydrological analyses

A land surface analysis (including runoff), comprised of 24 ensemble members at 2.5 km resolution, is produced by driving the Surface Vegetation Snow land surface scheme (SVS; Alavi et al., 2016, Husain et al., 2016) with a meteorological analysis from the High Resolution Deterministic Prediction System (HRDPS) and an ensemble precipitation analysis, called the High Resolution

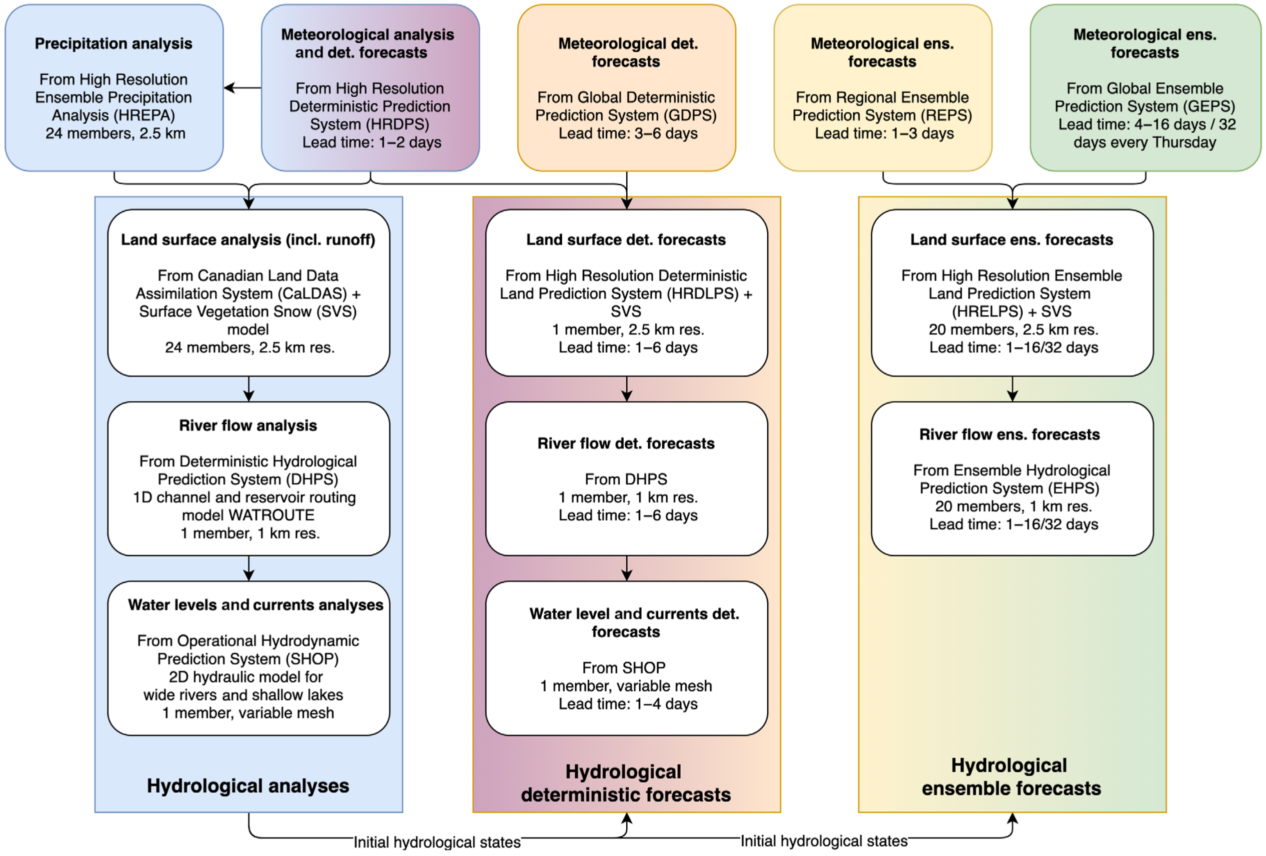

FIGURE 4 Flowchart of ECCC's Canadian Meteorological Centre (CMC) National Surface and River Prediction System (NSRPS). The different colors represent the various lead times of the analyses and forecasts. The latest update of the NSRPS system was implemented on December 1, 2021.

Ensemble Precipitation Analysis (HREPA; Khedhaouiria et al., 2020). HREPA assimilates ground-based and radar observations of precipitation. The SVS land surface scheme is additionally coupled to the satellite version of the Canadian Land Data Assimilation System (CaLDAS; Carrera et al., 2015), which assimilates observations of various variables from multiple satellites and systems, including skin and brightness temperatures from GOES-16 and GOES-17, soil moisture from the Soil Moisture and Ocean Salinity (SMOS; Kerr et al., 2012) satellite and the Soil Moisture Active Passive (SMAP; Entekhabi et al., 2010) mission, and snow cover from the National Ice Center's Interactive Multisensor Snow and Ice Mapping System (IMS; U.S. National Ice Center, 2004).

The outputs from the land surface analysis are fed into the Deterministic Hydrological Prediction System (DHPS; Durnford, Gaborit, et al., 2022). DHPS provides a single river flow analysis at 1 km resolution using the 1D channel and reservoir routing model WATROUTE (Kouwen, 2018). DHPS represents diversions within and between river basins as well as management rules of regulated reservoirs (using the Dynamically Zoned Target Release [DZTR] reservoir model; Gaborit et al., 2022; Yassin et al., 2019). Currently, the basins covered by DHPS in operations are the Yukon, Mackenzie, Churchill and Nelson Rivers, the Great Lakes and St. Lawrence River system, and the terrain draining into the Gulf of St. Lawrence. To constrain the analyses, river flow observations from ECCC, the United States Geological Survey (USGS) and the provincial networks of Alberta and Québec are assimilated into DHPS. Water level and current analyses are provided by the Operational Hydrodynamic Prediction System (SHOP).

3.1.2 | Hydrological deterministic and ensemble forecasts

The High Resolution Deterministic Land Prediction System (HRDLPS), in combination with the SVS land surface scheme, provides deterministic forecasts of the land surface (including runoff) twice daily, for up to 6 days lead time, at 2.5 km resolution. HRDLPS is driven by meteorological deterministic forecasts from HRDPS for days 1–2, and from the Global Deterministic Prediction System (GDPS) for days 3–6. The land initial conditions are obtained from DHPS (described above). Deterministic forecasts of river flows are provided by DHPS twice daily, for up to 6 days lead time, at 1 km resolution, driven by outputs from HRDLPS. Deterministic forecasts of water levels and currents are provided by SHOP for days 1–4, updated four times per day. SHOP forecasts are initialized with states from the SHOP analysis and fed with tributary flows from the DHPS deterministic forecasts, and winds from HRDPS.

Ensemble forecasts (20 ensemble members) of the land surface and river flows are currently in development. They are driven by meteorological ensemble forecasts from the Regional Ensemble Prediction System (REPS) for days 1–3 and from the Global Ensemble Prediction System (GEPS) for days 4–16 (extended to 32 days on thursdays). Ensemble water level and current forecasts will be added in the future.

The CMC has recently investigated the usefulness of monthly and seasonal numerical prediction systems to predict the potential of floods. After several years of subjectively evaluating estimates of surface runoff from GEPS, forecasters at CMC concluded that monthly and seasonal numerical prediction systems have value. For instance, before the 2019 spring floods in the Ottawa and St. Lawrence River basins near Montréal (draining into the Atlantic Ocean), the potential for flooding was predicted for the region 2 weeks in advance. As time progressed, the warning was refined both in terms of location and severity. Based on this experience, surface runoff from both the global and regional ensemble prediction systems (GEPS and REPS, respectively) were added to the Canadian Centre for Meteorological and Environmental Prediction (CCMEP)'s Vigilance series. These predictions are now used operationally to alert the Government Operations Centre of possible extreme weather and impacts.

3.1.3 | NSRPS system modularity

The NSRPS system is physically coherent across components (i.e., use of the same national grid, geophysical databases, and model versions). This enables combining several products from various components of the system. Another benefit of the system's modularity is that individual components can be updated separately. Moreover, the performance of downstream systems depends on the performance of upstream components and can prompt additional research and development. Thus, NSRPS acts as a numerical laboratory, where experimental developments can then be added to CMC's coupled atmospheric-land-ocean operational prediction systems.

3.2 | Global Water Futures: Advancing the research of hydrological modeling and forecasting

The GWF core modeling team made several contributions to advance the science and practice of large-domain hydrological modeling and prediction in Canada. Efforts are ongoing to enhance national forecasting capabilities. Some key advances include:

- Developing ensemble meteorological datasets for North America and the globe (Tang et al., 2020; 2021; 2022);
- Advancing methods to simulate snow processes, using unstructured grids to produce hillslope-scale simulations of dominant snow processes (i.e., snowpack energetics, blowing snow, redistribution, avalanching, sublimation, melt) across large geographical domains (Marsh et al., 2020; Vionnet et al., 2021);
- Developing a new snowpack and snow cover forecast system, based on the Canadian Hydrological Model (CHM)'s snow redistribution, and melt modules (Marsh et al., 2020) driven by 2.5 km HRDPS forecasts (Figure 4). The test product, called SnowCast, is available online (www.snowcast.ca) and provides predictions in the mountains of western Canada at scales down to 50 m.
- Establishing modular approaches to hydrological modeling for dominant hydrological processes across different sub-domains (e.g., vegetation, snow, glaciers, soil, groundwater) (Clark et al., 2021; Pomeroy et al., 2022).
- Improving the robustness and efficiency of the numerical solutions in land models, obtained by separating the physical representations from numerical solutions and implementing advanced numerical solvers (Clark et al., 2021);
- Developing a flexible model configuration toolbox to accelerate the implementation of large-domain hydrological models (Gharari et al., 2021; Knoben et al., 2022);
- Developing agile parallelization methods capable of handling heterogeneous computing loads and bottlenecks in the downstream reaches of large river networks (Mizukami et al., 2021);
- Adapting a physically based hydrological-glaciological land surface scheme (MESH) to mountain and glaciated basins, frozen ground, and large lakes. Applying it for operational flood forecasting for the Yukon River basin and several of its tributaries (Pacific Ocean drainage basin), with critical assistance and forecasts from ECCC (Elshamy et al., 2022; Elshamy, Loukili, et al., 2020). The system was provided to the Government of Yukon along with training for local

hydrological forecasters. It is now being operationalized for Yukon Environment's flow forecasting purposes using Delft-FEWS. This partnership illustrates that academia, government and other industrial and community partners can strike powerful collaborations to create advanced forecasting systems;
- Advancing operational forecasting of ice-jam floods. Due to the complexities of forecasting ice-jam floods (see Section 2.1), these forecasts are rarely provided. The MESH model coupled to a river ice model were embedded in the forecasting system for the lower Churchill River in Labrador (draining into Hudson Bay and Labrador Sea), one of the world's first operational ice-jam flood forecasting systems (Lindenschmidt, 2020). Real-time ice-cover breakup and ice-jam flood forecasting systems based on MESH were also developed and tested for the Athabasca River in Alberta (draining into the Arctic Ocean, e.g., Lindenschmidt et al., 2019; Rokaya et al., 2020).

Research is also underway as part of GWF, on advancing methods for:

- Developing model components, including improved representation of permafrost (Elshamy, Princz, et al., 2020), glaciers (Pradhananga & Pomeroy, 2022; Tesemma et al., 2020), prairie potholes (Clark & Shook, 2022; Shook et al., 2021), and incorporating reservoirs and irrigation (Tefs et al., 2021), abstraction and reservoir management (Yassin et al., 2019);
- River and lake routing, including the development of integrated river–lake hydrography datasets and the development of large-domain reservoir management models;
- Large-domain parameter estimation;
- Probabilistic hydrological prediction on timescales from seconds to seasons. While most provinces and territories are focused on sub-daily streamflow forecasting, GWF has been developing both statistical and process-based sub-seasonal to seasonal forecasting systems for North America, in partnership with ECCC and the National Center for Atmospheric Research (NCAR, The United States). These forecasts on longer timescales will be beneficial for water management, particularly for reservoir operations, agriculture, and drought prediction;
- Developing a model-agnostic ice-jam forecasting system, that could be coupled with any hydrological model for any region across Canada;
- The (ensemble) assimilation of snow data in operational forecasting. GWF researchers are developing an improved data assimilation system, to generate distributed SWE (snow water equivalent) forecasts for ungauged basins and to improve hydrological forecast skill (Lv et al., 2019; Lv & Pomeroy, 2020). These advances could directly contribute to the forecasting needs of provinces and territories.

The underlying development philosophy is model-agnostic—while different models are suited to different applications, and modeling groups are attached to their in-house models, we also recognize that many modeling groups share similar challenges. Much can be done to share codes and concepts across development groups and increase the effectiveness and efficiency of the overall hydrological modeling workflow (see Knoben et al., 2022 for a full discussion on model-agnostic workflows). GWF developments are hence focused on general tools and approaches that can be used across a myriad of different modeling groups.

3.3 | Collective engagement in forecasting: Building a community of practice

River forecast centers are primarily operationally focused with little time to explore, develop, and implement experimental products or to directly engage with research groups. However, the forecasting landscape is changing, for example, with the use of remote sensing products, global climate models, diverse hydrological models, and programming packages. This presents challenges in balancing the primary requirement for real-time forecasting operations with the additional need to allocate time and resources to conduct research, investigate new products, perform suitability assessments, and improve systems through new innovations or products (Zahmatkesh et al., 2019). Nevertheless, some provinces do not have the same limitations in this regard and have partial to adequate resources to explore and engage in varying levels of research and development activities while supporting their operational duties.

Considering the expanding skill set required to produce forecasts, with the sometimes-limited operational capacity within individual river forecast centers to meet these expanding demands, a community of practice could play a pivotal role in leveraging the expertise and experience in the different river forecast centers across Canada (Pietroniro et al., 2021). As part of this initiative, two national forecasting workshops/forums involving federal agencies, provinces and territories, academia, industry, and other national and international partners and collaborators were organized jointly by ECCC and GWF in 2019 and 2021. During these workshops, participants discussed and identified challenges for flood forecasting

FIGURE 5 Graphics made during live sketching at the Canada Flood Forecasting Forum 2021 by Louise Arnal. Each graphic shows a challenge highlighted by participants during the workshop.

(Figure 5). Namely, they have expressed a strong desire to be able to connect with other practitioners and engage in ongoing constructive conversations, particularly focused on addressing immediate priorities and needs. Common needs were identified for specialized information on river ice dynamics and snowpack for snowmelt-driven and rain-on-snow driven flow events and water supply forecasts. Additionally, a common and more efficient approach to data flow and characterizing river basins for model setup and parameterization was seen as useful. Other identified hydrotechnical topics of national importance include ice-jam flooding, flood mapping for the purposes of land use planning and flood response, seasonal hydrological forecasting, flash flooding, alpine debris flooding, and forecast communication (Pietroniro et al., 2021).

Work is now underway to create a space for practitioners to discuss challenges, collaborate on developing or leveraging solutions, and identify and recommend specific subjects for further study. The community of practice aims to facilitate sharing of information on available products, tools, applications, common experiences, best-practices, and evolving ideas across jurisdictions to improve flood forecasting across Canada (Pietroniro et al., 2021). While a wide variety of issues and approaches to flood forecasting exist across the country, there are some common elements as well (see Section 2). Although different jurisdictions may choose to deal with the same issue differently, there are still benefits to continuing to understand what is working and what is not, so that others facing similar issues can learn from previous knowledge and experience. Particularly, jurisdictions with limited capacity can benefit from the knowledge and experience residing in other jurisdictions who have faced similar issues and/or with more established forecasting systems.

4 | FUTURE DIRECTIONS FOR OPERATIONAL FLOOD FORECASTING IN CANADA

This section presents a series of future directions for the global flood forecasting community, as well as for flood forecasting in Canada more specifically. These are shaped by the GWF and NHS experiences and build on the international peer-reviewed literature. Investments in institutions and technology are required to enable river forecast centers in Canada to integrate large-domain information with local domain forecasts. Key challenges identified by Zahmatkesh et al. (2019) remain pertinent, including limited data availability, modeling capacity, reliability, and uncertainty in forecasting, communication (particularly interjurisdictional), and human resources (employment and retention of staff to build institutional memory). This will require tackling outstanding challenges along the forecasting process, as highlighted by larger community efforts such as HEPEX. In addition, it is critical to define more effective roles for human forecasters in the flood forecasting process. Underlying these challenges is the need for a community of practice, to share codes, concepts, best practices, and tools more effectively across different operational flood forecasting groups.

4.1 | Cooperation and governance for large-domain modeling and forecasting

The need for large-domain forecasting may appear counterintuitive given the constitutional and the hydrological realities present in a large country like Canada. Local knowledge of hydrology and hydraulic conditions is fundamental in producing robust and reliable forecasts at the community level. However, there remain compelling reasons for a more wholistic and national approach to flow guidance in a country such as Canada. Historically, Canada has been built on a cooperative federalist model, which relies on cooperation at provincial/territorial and federal levels to bring efficiency and economies of scale and help deliver equitable services across Canada. In the area of water resources, the NHS, and particularly the WSC, have adopted this cooperative federalist model since 1975: hydrometric monitoring is managed as a cost-shared partnership (see Section 2.2). In this instance, entities that are best placed to carry out systematic flow measurements, training and to advance the science of hydrometry are co-managed so that standards are consistent, but the operator may vary from a province/territory to the other. This cooperation minimizes costs while maintaining consistent and comparable measurements across the country.

A similar argument could be made for flood forecasting. A national flow guidance system can provide useful deterministic and probabilistic scenarios to the local agencies, which are then best placed to provide locally contextualized forecasts and assist local authorities in developing emergency plans to mitigate the consequences. Decisions to evacuate communities or provide mitigation through sandbagging or other operations are expensive and must be risk-managed at the local level where consequences and risks are understood. There is clearly a need for local bespoke systems at the provincial/territorial (or even city/municipality) level to enable decision-making. Nevertheless, national flow guidance can be useful and essential in that context, supporting local systems, as well as the information flow back to the national level for risk assessment and emergency management. A relevant international example is the Copernicus Emergency Management Service (CEMS) European and Global Flood Awareness Systems (EFAS and GloFAS, respectively; see Table 1), which provide early warning and monitoring information for floods and droughts across Europe and globally (Emerton et al., 2016). In Europe, the EFAS hydrometeorological forecasts and flood warnings and disseminated to the relevant national and regional authorities, which subsequently use them alongside their bespoke systems to issue flood warnings to the public. The EFAS flood warnings are not communicated to the public directly to respect the responsibilities for national and regional entities to communicate the official flood forecasts.

An alternative is a two-stage action approach, whereby a large-domain system is used for decision-making at longer lead times and local information and systems are used for short-term decision-making (Bischiniotis et al., 2019). This two-stage action approach is being explored in Bangladesh (the Brahmaputra River basin) where GloFAS forecasts are used for the pre-activation of flood anticipation measures at longer lead times and the Bangladesh Flood Forecasting and Warning Centre's forecasts are used at shorter lead times (Stephens, 2021). Another example is in England and Wales where the Flood Forecasting Centre uses a national forecasting system to generate outlook products at longer lead times while the Environment Agency centers issue flood warnings based on local systems and tools (Arnal et al., 2020; Stephens & Cloke, 2014).

There are several reasons to adopt a national system for Canada. First, it would be cost-prohibitive for each province and territory in Canada to develop, test, and operate individual forecasting systems tied to NWP infrastructure. The current fragmented nature of flood forecasting in Canada does not necessarily allow for an individual jurisdiction to mobilize knowledge and advance local capabilities (see Section 2.2). A Canada Water Agency could tackle the availability of resources at a national level to support the river forecast centers' research and development activities, alongside their operational duties. As an example, EFAS, developed at the European Commission's Joint Research Centre, in close collaboration with national hydrological and meteorological services and other entities, provided an ideal context and the resources necessary to efficiently operationalize the state-of-the-art science across a large domain (Smith et al., 2016).

The second justification for a national system is that there is likely going to be a flood somewhere in Canada every year. However, investment in flow and flood forecasting in Canada has historically often been tied to the occurrence of large flood events, with under-investment in flood-free periods. It is well known in the community that investment in data systems, improved flow and flood modeling, and staffing are sometimes tethered to recent history of extreme events as opposed to a longer-term strategic planning effort (Arnal, 2016). For instance, the province of Saskatchewan developed a computerized prairie basin flood model after the disastrous floods of spring 1974 in southern Saskatchewan. After several decades without extreme flooding, the model became disused, and the province did not develop this capability again until after the extensive floodings of 2011 and 2014. Maintaining expert forecasters and institutional memory has been difficult in this industry, where experience is vital.

Finally, a national system is needed because the research, development, and operation of large-domain modeling and flow guidance systems cannot be piecemeal. The research that supports the development of flood forecasting models, and the development, version control, and benchmarking required to assess improvements require coordination and the expertise present at national and international levels. Aligning expertise in larger forecasting centers but being mindful of local realities and the complexities of hydrological regimes, will require both top-down and bottom-up approaches to build credibility and trust. It will be important that an international/national/regional system articulates accountability and responsibility of individuals at each level in the forecasting chain.

As climate change is altering flood occurrence in Canada (Buttle et al., 2016), there is a strong need to adapt flood forecasting systems to increase community resilience and reduce economic losses. In this context, a continental flood prediction system provides a consistent historical baseline from which to measure change. Moreover, continental prediction is vital to support Canada-wide climate change mitigation and adaptation planning (Stadnyk & Déry, 2021). A national flow guidance system for Canada falls under the umbrella of the Emergency Management Strategy for Canada (Government of Canada, 2022) and is essential in meeting the targets of the UN Sendai Framework for Disaster Risk Reduction (2015–2030), by:

- Providing coordinated and complementary flood forecasts to provinces, territories, municipalities, stakeholders, and rightsholders.
- Supporting underserved communities and smaller jurisdictions with limited and fragmented early warning systems and data infrastructures.
- Enabling international cooperation for sharing flood hazard, monitoring, and early warning information.

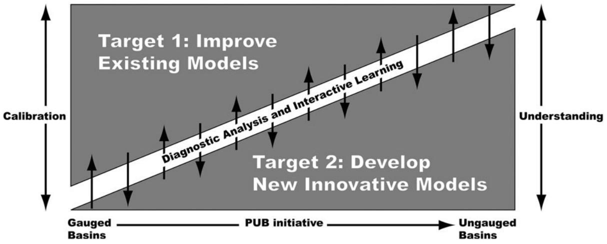

FIGURE 6 Targets of a paradigm change in hydrological prediction by improving existing and developing new innovative models that transition from calibration to understanding, from the International Association of Hydrological Sciences (IAHS) Decade for Prediction of Ungauged Basins (PUB). Figure taken from Sivapalan et al. (2003).

4.2 | Cold regions research and forecasting needs

A key challenge to flood forecasting, especially in cold regions such as Canada, is to improve the model representation of relevant hydrological processes in the regions where the model is applied. Many operational flood forecasting systems, including the ones summarized in Table 1, rely on rainfall-runoff models which may not dedicate sufficient attention to cold region hydrological processes. Notably, blowing snow and avalanching, detention storage in wetlands, storage and transmission of water in partially frozen soil and permafrost, coupled thermodynamic and hydrological processes in lakes and rivers, thermodynamics of snowmelt and ice melt, and the formation and breakup of river ice. There is an outstanding need to identify and address hydrological model weaknesses in cold regions through multivariate evaluation using observations on scales from hillslopes (e.g., research basins) to continents (e.g., satellite estimates of snow-covered area and total water storage).

More work is required to improve the extent to which a model faithfully represents the dominant processes in the region where it is applied, especially in basins where hydrometeorological observations are sparse or nonexistent (Figure 6). A key development in other regions is Artificial intelligence (AI)/machine learning (ML) approaches. However, AI/ML methods are primarily data driven and so are challenged by sparsely gauged and ungauged basins in Canada (Gauch et al., 2021). Additionally, changes in flood generation processes, such as the role of snowmelt, glacier melt, and river ice breakup in flooding, can make it more difficult to use data-driven models for predictions. In response to the persistence of systems that rely on data-driven mimicry such as AI/ML, the International Association of Hydrological Sciences (IAHS) developed the Decade for Prediction of Ungauged

Basins (PUB) in 2003 (Sivapalan et al., 2003). PUB aspired to develop new predictive approaches based on a deeper and more complete understanding of hydrological functioning and heralded a change of paradigm in hydrology from one dominated by calibration to one based on understanding (Pomeroy et al., 2013). Nevertheless, modern AI/ML systems now incorporate process-based models, providing physical constraints on predictions and making more effective use of big data in the prediction process, and hence increasing the potential for AI/ML methods in the sparsely-gauged Canadian landscape.

Despite being a major concern in Canada, forecasting of ice-jam flooding is still in its infancy from an operational perspective. There has been tremendous research progress made in the last few decades, with models ranging from simple statistical to complex hydraulic systems available to predict ice-cover breakup timing, flow, and backwater staging (see Section 2.1). Much of this research was compiled by the Committee for River Ice Processes in the Environment (CRIPE). Recent years have also seen a surge in applications of artificial neural networks and other ML techniques with advances in computing power and technology. However, the computational resources required to simulate ice-jam events is still limiting the application of these research advances into operational practice. Model codes need to be parallelized to make optimal use of computational resources. Furthermore, most of the existing methods used for ice-jam flooding are site-specific and only applicable locally. Advances in model-agnostic couplers are needed to embed river ice models into existing forecasting frameworks, allowing for swift adoption of any model of choice (see Section 3.5). Additionally, model codes should be made open source to promote further uptake by operational forecasters (Knoben et al., 2022). Much work is still needed on developing large-domain, model-agnostic, and end-user friendly approaches for operational forecasting.

4.3 | The increasing wealth of data and products

There has recently been a diverging trend in data availability whereby traditional in-situ data sources are decreasing globally, while novel data sources from remote sensing and re-analysis are on the rise (Wu et al., 2020). Re-analysis products have a valuable role in hydrological assessment and model development in areas of Canada where in-situ meteorological measurements are sparse and records are short (Asong et al., 2020). Moreover, there is increasing understanding of the value in incorporating different information sources for early warning.

Citizen science and crowdsourcing (i.e., the involvement of citizens in the scientific process) have received increasing attention in the last decade. In a recent study, See (2019) provides a comprehensive review of citizen and crowdsourcing applications in flooding research. Notable applications include data mining of social media posts, crowdsourced images, and the use of mobile phone applications to collect ground observations (e.g., the CoCoRaHS volunteer rain, hail, and snow network across North America; Reges et al., 2016), to detect and confirm flood events, for river flow estimation or real-time flood mapping (Le Coz et al., 2016), and to provide post-event analyses. Mazzoleni et al. (2017) demonstrated the added value for flood forecasting of often asynchronous and inaccurate crowdsourced data, in addition to more traditional observation networks.

The increasing availability of datasets is encouraging, but data provision alone does not guarantee added value to the forecasting community. While remote sensing data increasingly provides valuable information to hydrology, there are known impediments to their use in operational forecasting (McCabe et al., 2017). Aside from the need for expert knowledge in the acquisition, processing, and interpretation of remote sensing imagery, the quantity and processing time can be prohibitive for use in operational settings. Caution and guidance in the applicability of novel products are also needed. An example would be the readily available GlobSnow-2 SWE product (Takala, 2011), where despite its operational availability, daily latency, and wide spatial coverage, the product is likely not suitable for use in hydrological forecasting due to identified biases near the end of the snow accumulation period and during melt (Casson et al., 2018; Larue et al., 2017).

The last decades have seen unprecedented advances in flood forecasting around the globe (Wu et al., 2020), which have translated into bespoke large-domain operational forecasting systems (Table 1). Through the wide dissemination of flood forecast products, large-domain flood forecasts provide vital early warning information for potential upcoming floods, both locally and regionally, notably in transboundary basins or in basins where no local system is available (Alfieri et al., 2013). Several different forecasting products are now publicly and freely available within the Canadian domain from various government, academic, and industry groups. This provides the operational flood forecasting practitioners across Canada with additional tools and services to leverage to improve their forecast if they have the internal resources and expertise to do so. However, it also creates a challenge in communicating the more authoritative forecasts amongst the multiple available forecasts and contextualizing the forecast messaging. A promising approach to tackle this is the framework being developed by Odry et al. (2021) for merging forecasts from two hydrological forecasting systems. Their initial findings from merging forecasts from the federal and provincial governments in Québec are encouraging and suggest that the merged forecasts remain at least as good as the raw local forecasts. The increasing wealth of data and products can promote healthy competition and provide users with a diversity of information to help them inform their decisions.

4.4 | Knowledge mobilization and communication

While scientific progress in flood forecasting is undeniable, the communication of knowledge from science to operations, decision-makers, and the public is still lagging, with considerable repercussions on the resilience of society to extreme events. Two recent, catastrophic flood events can be used as specific examples: the July 2021 western Europe floods, and the November 2021 British Columbia flood. As noted by Cloke (2021), in the western Europe event "*the whole system designed to save lives by ensuring people act on warnings before floods arrive, did not work as it should have done. It may be that individual parts of the system worked exactly as they were designed, and it is certainly true that forecasts were accurate, and there were some warnings issued through official channels. In some areas, many authorities did act in time, to evacuate people, erect temporary flood defenses, and move vehicles to higher ground. But this clearly did not happen everywhere.*" In the British Columbia flood in November 2021, parts of southern British Columbia recorded between estimated one in 50- and one in 100-year rainfall events, triggered by an atmospheric river delivering about 1 month's precipitation in a matter of hours. This rain fell on deep mountain snowpacks in some basins. Although evacuation and flood warnings were issued, the widespread flooding was so extreme that it triggered mudslides and damage to the transportation infrastructure, which, coupled with high water levels, prevented the safe effective evacuation of people and livestock, ultimately leading to the loss of human life and thousands of animals.

Both of these events underscore the importance of early warning systems that are designed to give time for communities to evacuate and time to mobilize flood defense mechanisms. Warning times are already short in mountainous regions prone to flash runoff due to steep, rocky slopes, and limited transportation routes through mountain passes. These events further highlight the importance of coherent and coordinated communication amongst data collection systems, forecasters, operators, and the public. In this context, knowledge mobilization between science and practice would help foster coherent and coordinated early warning. The establishment of a community of practice, as introduced in Section 3.6, is an important element of these knowledge mobilization efforts.

The need for a community of practice is pronounced in Canada due to the delegated responsibility for flood early warning to provinces and territories. After the 2019 Canadian flood forecasting forum, the need to systematically share information on what practices are working, what information sources are becoming available and what improvements are needed was identified. The community of practice should therefore foster and enhance cooperation amongst the river forecast centers as well as with the federal government and other operational and research groups to enhance the forecasting services available in Canada. This would ensure that policy and practice are kept up to date with the latest scientific improvements and developments for a better understanding of what is available to assist them in developing or refining their current forecasting systems (Neumann et al., 2018). Following the European example, whereby EFAS was built and is developed in close collaboration with national and regional authorities and experts from different members, there is an opportunity for a Canada Water Agency to provide a neutral ground to foster communication amongst the various agencies responsible for flood forecasting within Canada.

This systematic communication ensures that development efforts focus on the identified needs of the community of practice. The limited experience in Canada with the recent development of the flood forecasting community of practice has already focused research areas of mutual interest and national importance that require attention (see Section 3.6; Pietroniro et al., 2021). These focus areas inform areas pertinent to Canadian realities and may also help inform the focus of the global community in research and development shortcomings that are perhaps not readily considered in academia. Although certain jurisdictions may not prioritize all these issues similarly, there is an obvious need for cooperation nationally to develop additional solutions in response to them. The proposed Canada Water Agency could be uniquely positioned to aid in pursuing these solutions, through facilitating solution development with industry, academia, and international experts or directly developing the solutions themselves in partnership with interested provinces and territories.

Another important realization is knowledge mobilization with respect to the communication of forecasts. Forecasters are not only responsible for developing accurate forecasts, but they must also communicate the forecasts to client groups that may not have much or any water resources expertise. In addition, as ensemble forecasts become ubiquitous, communicating them effectively to emergency responders that may not have a well-developed understanding of probabilities or uncertainties provides another challenge that forecasters and decision-makers must overcome (Arnal et al., 2020; Cloke & Pappenberger, 2009; Demeritt et al., 2010; Pappenberger et al., 2012; Ramos et al., 2013). The dissemination of probabilistic information is currently an obstacle to their operational implementation in Canada (see Section 2.3). As raised by Arnal et al. (2020), a yes/no decision has to be made based on probabilistic information and decision-makers interviewed in the UK expressed the fear of being "blamed" for that decision. In this context, Das et al. (2022) argue for the need of a decision support system to provide a rational basis on which flood protection decisions and flood management policies can be made at the local, regional, and national levels. A Canada Water Agency could help establish such a system nationally, to articulate accountability and responsibility of individuals in the flood early warning chain.

Forecasts need to be communicated clearly to local decision-makers to enable adequate anticipatory action (Cools et al., 2016). Operational flood forecasting systems generally offer a combination of maps, hydrographs, and text updates to their users (e.g., forecasters, decision-makers, humanitarian actors, and the public) via web platforms (Table 1). To enhance the usefulness of flood early warning systems locally, the communication of actionable expected flood risks and impacts is also crucial (Apel et al., 2022). As an example, flood inundation mapping is an avenue being increasingly explored for operational implementation within existing or new flood forecasting systems—for example, see the EFAS rapid flood mapping (Dottori et al., 2017) and the Google inundation model (Nevo, 2020).

Flood forecasting and early warning is a complex chain with various actors (Golding et al., 2019). Effective science communication should therefore aim to ensure that the scientific message is accessible to a broad and diverse audience. Using inclusive and creative media, such as visual art, poetry, serious games, and citizen science, can help to generate dialogs with a wider non-expert audience. It can help make science more accessible overall and increase community resilience by promoting communication, awareness raising, and engagement (See, 2019; Illingworth, 2020; Speight et al., 2021; van Loon et al., 2020). Creative methods can additionally help build community resilience to hazards by enabling people to imagine future risk and possible preventive actions (van Loon et al., 2020).

A Canadian community of practice would be instrumental in providing essential perspectives on the challenges facing the provincial and territorial forecasting agencies with respect to communicating uncertainty, likelihood, and potential severity of impending flood events to emergency managers and the public. Furthermore, solutions to those challenges can be developed within a more nationally or internationally consistent framework, while ensuring they are responsive to the regional and local communication needs.

5 | CONCLUSIONS

Canada is addressing similar issues to many other countries in their pursuit of state-of-the-art flood forecasting services, namely: managing a proliferation of products, bridging the gap between local and large-domain information, modernizing the computational software for flood forecasting (including model-agnostic approaches), developing a community of practice for flood forecasting, and defining the role of human forecasters in the prediction process. At the national scale Canada has the unenviable challenge of predicting floods across a large and diverse, cold-regions dominated landscape. These challenges also provide a unique opportunity for the Canadian community to learn from its local and international partners, while contributing its expertise to the global forecasting community. There is an ongoing transformation internationally in flood guidance systems, and agencies like the World Meteorological Organization are striving for seamless large-domain Earth System modeling efforts that meet the needs of the local communities. The realities in the future will be hydrological forecasting centers established at key locations around the globe that will provide global flood guidance information. The recent investments in hydrological science in Canada are creating opportunities for Canada to make greater contributions in developing the next generation of flood forecasting systems.

Canada's role in the large-domain flood forecasting landscape has changed markedly in recent years. As the impacts of climate change are becoming more acute and the costs of flooding are rising dramatically (Office of the Parliamentary Budget Officer, 2016), there is a need to co-develop systems that can do a better job at communicating and mitigating flood risks for all Canadians. Starting in 2018, the Meteorological Service of Canada and the National Hydrological Service were tasked as federal entities to develop a national flow guidance system for

Canada. Alongside this development, the Global Water Futures program has focused on addressing Canadian water challenges through the development of new models, hydrological processes understanding, and knowledge mobilization efforts. These initiatives have enabled the ongoing development of a coherent approach to flood forecasting at the national level that respects the local hydrological realities, while ensuring that state-of-the-art flood forecasting science and technology are made available to decision-makers and stakeholders across the country. Alongside technical developments, the recent establishment of a community of practice to bring together various local and national perspectives, and the announcement of a Canada Water Agency in the Speech from the Throne in November 2021 (Government of Canada, 2021a) provide the foundation for improved flood prediction in Canada.

The following series of recommendations are made to move towards a more coherent flood forecasting framework for Canada. These recommendations are also germane for other large-domain flood forecasting efforts around the world.

- A coherent national flood forecasting framework should be developed to coordinate local, regional, and international efforts, and to enable the operationalization of state-of-the-art science and technological advances in flood forecasting.
- The national framework should follow both a top-down and bottom-up approach to be mindful of local realities and to build credibility and trust between academia, policy, and practice.
- The national framework will need to articulate accountability and responsibility of individuals in the flood early warning chain.
- While the increase in availability of data products is encouraging, provision alone does not guarantee added value to the forecasting community. The national framework should encourage forecasters and decision-makers' access to a variety of data products, while clearly communicating the authoritative forecast.
- The community of practice should facilitate cooperation between industry, academia, and international experts, and must be instrumental in providing essential perspectives on the challenges facing the provincial and territorial forecasting agencies.
- Creative methods and educational campaigns could be explored to help build societal resilience to floods through improved communication and public engagement.

The need for coherent flood forecasting services now has renewed urgency. Recent flood events in British Columbia and Newfoundland in November 2021, alongside increasing disaster-related costs across the country, are highlighting the importance of a more coherent flood forecasting effort in Canada. With the cleanup from the British Columbia flood event now underway, questions additionally arise regarding the resilience of existing supply chains, transportation networks, as well as regarding the design standards that should be used to rebuild given that the frequency of severe events is increasing. A new Canada Water Agency is well-placed to successfully deal with Canada's outward looking aspiration to contribute to global forecasting capabilities, while ensuring its important national obligations to keep Canadians safe.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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APPENDIX A

A.1 | Glossary of Canada-specific acronyms

Acronym	Meaning
CaLDAS	Canadian Land Data Assimilation System
CaPA	Canadian Precipitation analysis
CCMEP	Canadian Centre for Meteorological and Environmental Prediction
CHM	Canadian Hydrological Model
CMC	Canadian Meteorological Centre
DHPS	Deterministic Hydrological Prediction System
ECCC	Environment and Climate Change Canada
EHPS	Ensemble Hydrological Prediction System
GDPS	Global Deterministic Prediction System
GEPS	Global Ensemble Prediction System
GWF	Global Water Futures
HRDLPS	High Resolution Deterministic Land Prediction System
HRDPS	High Resolution Deterministic Prediction System
HRELPS	High Resolution Ensemble Land Prediction System
HREPA	High Resolution Ensemble Precipitation Analysis
MESH	Modélisation Environnementale communautaire - Surface Hydrology
MSC	Meteorological Service of Canada
Nav Canada	Canadian civil air navigation system operator
NSRPS	National Surface and River Prediction System
OHPS, commonly known as SHOP	Operational Hydrodynamic Prediction System
RDPS	Regional Deterministic Prediction System
REPS	Regional Ensemble Prediction System
SPS	Surface Prediction System
SVS	Surface Vegetation Snow
WISKI	Water Information Systems by KISTERS
WSC	Water Survey of Canada