Received: 27 July 2021 | Revised: 14 March 2022 | Accepted: 16 March 2022

DOI: 10.1002/hyp.14557

TOWARDS MORE CREDIBLE MODELS IN CATCHMENT HYDROLOGY TO ENHANCE HYDROLOGICAL PROCESS UNDERSTANDING

WILEY

Advances in modelling large river basins in cold regions with Modélisation Environmentale Communautaire—Surface and Hydrology (MESH), the Canadian hydrological land surface scheme

Howard S. Wheater[1,2,3] | John W. Pomeroy[1,2] | Alain Pietroniro[4,5] | Bruce Davison[4] | Mohamed Elshamy[1,2] | Fuad Yassin[1,2] | Prabin Rokaya[1,2,8] | Abbas Fayad[1,2] | Zelalem Tesemma[1,2] | Daniel Princz[2,4] | Youssef Loukili[1,2] | Chris M. DeBeer[1,2] | Andrew M. Ireson[2] | Saman Razavi[2] | Karl-Erich Lindenschmidt[2] | Amin Elshorbagy[6] | Matthew MacDonald[1,7] | Mohamed Abdelhamed[2] | Amin Haghnegahdar[2] | Ala Bahrami[2]

[1]Centre for Hydrology, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

[2]Global Institute for Water Security, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

[3]Department of Civil and Environmental Engineering, Imperial College London, London, UK

[4]National Hydrology Research Centre, Environment and Climate Change Canada, Saskatoon, Saskatchewan, Canada

[5]Schulich School of Engineering, University of Calgary, Calgary, Alberta, Canada

[6]Department of Civil and Geological Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

[7]School of GeoSciences, University of Edinburgh, Edinburgh, UK

[8]Watershed Resilience and Transboundary Waters, Alberta Environment and Parks, Edmonton, Alberta, Canada

Correspondence
Chris M. DeBeer, Centre for Hydrology, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.
Email: chris.debeer@usask.ca

Abstract

Cold regions provide water resources for half the global population yet face rapid change. Their hydrology is dominated by snow, ice and frozen soils, and climate warming is having profound effects. Hydrological models have a key role in predicting changing water resources but are challenged in cold regions. Ground-based data to quantify meteorological forcing and constrain model parameterization are limited, while hydrological processes are complex, often controlled by phase change energetics. River flows are impacted by poorly quantified human activities. This paper discusses the scientific and technical challenges of the large-scale modelling of cold region systems and reports recent modelling developments, focussing on MESH, the Canadian community hydrological land surface scheme. New cold region process representations include improved blowing snow transport and sublimation, lateral land-surface flow, prairie pothole pond storage dynamics, frozen ground infiltration and thermodynamics, and improved glacier modelling. New algorithms to represent water management include multistage reservoir operation. Parameterization has been supported by field observations and remotely sensed data; new methods for parameter identification have been used to evaluate model uncertainty and support regionalization. Additionally, MESH has been linked to broader decision-support frameworks, including river ice simulation and hydrological forecasting. The paper also reports various applications to the Saskatchewan and Mackenzie River basins in western

Funding information
Canada Excellence Research Chairs, Government of Canada; Canada First Research Excellence Fund; Canada Foundation for Innovation; Canadian Foundation for Climate and Atmospheric Sciences; Environment and Climate Change Canada; Natural Sciences and Engineering Research Council of Canada

Canada (0.4 and 1.8 million km^2). These basins arise in glaciated mountain headwaters, are partly underlain by permafrost, and include remote and incompletely understood forested, wetland, agricultural and tundra ecoregions. These illustrate the current capabilities and limitations of cold region modelling, and the extraordinary challenges to prediction, including the need to overcoming biases in forcing data sets, which can have disproportionate effects on the simulated hydrology.

KEYWORDS
cold regions, hydrological modelling, large river basins

1 | INTRODUCTION

Cold regions, where snow, ice and frozen soils are major controls on the hydrological cycle, include much of the world's mid- to high-latitude regions and most mountainous areas. They thus form a large and important component of the Earth's climate and terrestrial systems and provide critical water resources to major populations in Europe, Asia and the Americas.

These regions are experiencing especially rapid warming, with profound effects that include glacier retreat, permafrost thaw, reduced snow depths and durations, and changing river flow regimes (Jimenez Cisneros et al., 2014). For example, DeBeer et al. (2016) report for western Canada that, over the last 60 years, winter air temperatures have increased by up to 6°C, the duration of snow cover has declined by 1–2 months, glacier retreat has accelerated, vast areas of permafrost have degraded or thawed, and the seasonality of flow regimes has changed. These rapid and continuing changes are having a dramatic effect on cold region environments and have potentially important feedbacks to climate and ocean circulations. They also present an existential challenge for the billions of people who depend on these regions for their water supply. There is therefore an urgent need for hydrological models that can represent the complexity of these process changes to address challenges that include modelling the earth system at global and regional scales, planning and management of uncertain water resource futures, and the forecasting and management of changing flood and drought risk.

Modelling the hydrology of cold regions poses distinct challenges. First, observations for forcing, calibrating, and evaluating models are limited, particularly outside agricultural regions. Ground-based observation networks are sparse and instrument performance is uncertain. Monitoring the most basic variables (e.g., snowfall or discharge of seasonally ice-covered rivers) is logistically and technically challenging, often resulting in large observational uncertainty. Second, there is a set of important challenges associated with cold region process representation. As water and energy fluxes are inextricably linked in these regions, hydrological models must include energy exchanges, associated, for example, with freeze–thaw phase changes and heat storage in soils, snowpacks and glaciers. Many process responses involve phase change and are thus sensitive to temperature changes around the zero-degree isotherm, which raises challenges for the required accuracy of forcing data and its interpolation, as well as for model process representation. Small temperature biases in forcing data can have large effects on process simulation and system behaviour.

There is a range of subtle, but important, scientific issues specific to these regions. For example, energy budgets in mountainous areas are strongly dependent on slope, aspect and elevation, raising challenges for spatial discretization. Blowing snow is an important lateral redistribution process in mountainous, arctic and prairie regions, but depends on local wind fields. Snow interception processes depend on evergreen canopy structure and must account for sublimation and unloading that can be strongly affected by meteorological variability. Glaciers and permafrost present their own distinct sets of modelling challenges, discussed below.

In this paper we briefly review some recent developments in modelling tools and applications, and discuss in detail improved process representations in the Canadian large-scale hydrological modelling system, Modélisation Environmentale Communautaire—Surface and Hydrology (MESH, Pietroniro et al., 2007), focusing on cold region processes and model applications across cold region basins in Western Canada, including mountains, boreal forest and prairies (Figure 1). MESH is a physics-based framework that can be applied at large scales as a stand-alone system or coupled with atmospheric models. The development of MESH has been based on multi-decadal collaboration between Environment and Climate Change Canada (ECCC) and the Canadian university sector. The research reported here has largely been co-developed at the University of Saskatchewan in collaboration with ECCC under the Canada Excellence Research Chair in Water Security and two national research programmes, the Changing Cold Regions Network until 2018 (CCRN; www.ccrnetwork.ca), and the Global Water Futures (GWF; www.globalwaterfutures.ca) project since 2016.

2 | SOME RECENT DEVELOPMENTS IN COLD REGIONS LARGE-SCALE MODELLING

In recent years, numerous efforts have been made to improve the representation of land surface hydrological processes in large-scale models, as well as model functionality and applicability. Widely applied modelling platforms, designed to link multiscale process

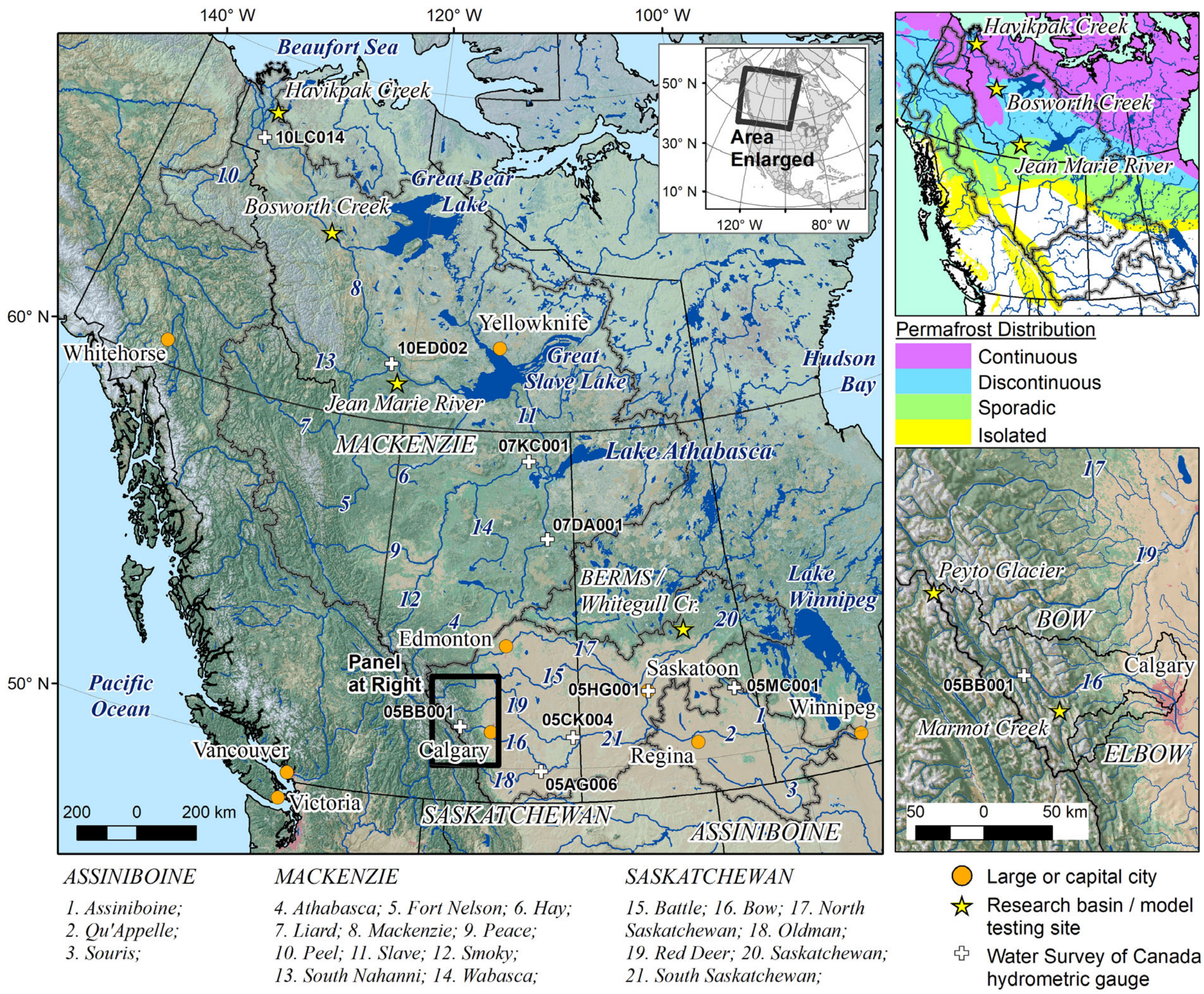

FIGURE 1 Major river basins and tributary river systems of the interior of western Canada, where MESH developments and testing described in this paper primarily occurred. Select Water Survey of Canada (WSC) hydrometric gauge locations and model testing sites referred to throughout the paper are indicated

models of the atmosphere and terrestrial hydrology, include the Weather Research and Forecasting (WRF)—Hydro (Lahmers et al., 2019) and the Global Environmental Multiscale (GEM)—Hydro (Gaborit et al., 2017) modelling systems, which have been used for prediction of flash floods, regional hydroclimate impacts assessment, seasonal forecasting of water resources and land-atmosphere coupling studies.

The representation of sub-grid spatial heterogeneity of both forcing data and land surface parameters is particularly important in mountain environments and is a crucial area of research and model development. Efforts to redistribute forcing data using topographic variability include work by Giorgi et al. (2003) and Nijssen et al. (2001). Representation of sub-grid spatial heterogeneity of land surface parameters has been addressed, for example, by de Vrese et al. (2016), and Liang and Xie (2001). The variable infiltration capacity (VIC) model, which is one example of a large-scale hydrological model developed as a land surface scheme for GCMs and used extensively to examine climate and hydrological impacts on river systems around the world, allows representation of sub-grid variability for precipitation and temperature through correction for topographic heterogeneity to improve simulations of surface hydrology (Hamman et al., 2018; Liang et al., 1994).

Cold region process representation of snow, frozen ground and soil processes have been addressed for smaller scales by the Cold Regions Hydrological Modelling Platform (CRHM, Pomeroy et al., 2007, 2016; Krogh & Pomeroy, 2021) and the Structure for Unifying Multiple Modelling Alternatives system (SUMMA, Clark et al., 2015; Clark et al., 2021). Glacier hydrology, snow redistribution by wind and gravity, snow, firn and ice melt energetics and glacier mass balance have been integrated for mountain glacier basins by CRHM with its CRHM-Glacier variant which is able to simulate the mass balance and hydrology of mountain glaciers in the Canadian Rockies. (Pradhananga & Pomeroy, 2022). Issues of modelling the hydro-thermodynamics of frozen ground and partially frozen soils have been examined by Walvoord and Kurylyk (2016), who noted the lack of implementation of these processes in large scale modelling. Snow transport, glaciers, permafrost and frozen soil processes have been a challenge for large scale hydrological modelling with many attempts at improvement across several models. Chadburn et al. (2015)

improved the physical permafrost processes in Joint UK Land Environment Simulator (JULES) by increasing the resolution and depth of the soil column, adding representation of organic matter thermal and hydraulic properties and improving the snow scheme. Wang et al. (2017) developed a coupled snow and frozen soil physics routine, improving snowpack internal process representation and soil water freezing and thawing. Qi et al. (2019) subsequently applied this within a distributed hydrological model for hydrological simulations over the Upper Yangtze River Basin on the Tibetan Plateau. Semenova et al. (2014) developed an analytical solution for heat transfer through frozen soils accounting for phase change and phase-dependent thermal conductivity. They integrated this within a hydrological model and were able to efficiently simulate soil temperature time series at multiple depths in soil with known permafrost conditions in the continuous permafrost zone of northeast Russia. However, many model applications suffer from too shallow a representation of soils and the underlying substrate, and too short a period of model initialization for appropriate representation of permafrost dynamics (Elshamy et al., 2020).

Attempts to improve the physical representation of glaciers include the VIC model, which has had a long history of progressive algorithm development. Early versions relied on a simple conceptual representation of glacier mass balance, relying on glacier masks and treating them as perennial snow (e.g., Schnorbus et al., 2014). The Pacific Climate Impacts Consortium (PCIC) in Canada developed a version of VIC with a more explicit representation of glaciers, VIC-GL, which simulates the accumulation and ablation of snow and ice directly and includes a coupled regional glacier dynamics model (Schoeneberg & Schnorbus, 2021). In a separate effort, Ismail et al. (2020) incorporated an energy balance glacier melt routine in VIC that includes a third bottom ice layer in addition to the two-layer snow model and represents ice thickness change as a function of mass balance. However, explicit representation of other glacier features, such as ice dynamics, meltwater routing through the changing glacial drainage system, or the densification of snow to firn to glacial ice have not yet been included.

Other attempts to broaden model applicability include the HYdrological Predictions for the Environment (HYPE) model, which was designed for small-scale to large river basin assessments of water resources and water quality (Lindström et al., 2010). Stadnyk et al. (2020) enhanced the Arctic implementation of HYPE through representation of prairie disconnected landscapes (i.e., non-contributing areas), added a method to generalize lake storage-discharge parameters across large regions, and incorporated frozen soil modifications. Tefs et al. (2021) incorporated a new reservoir regulation routine in HYPE, accounting for varying threshold water surface levels and outflow rules.

As the above discussion illustrates, over the past several decades there have been considerable advances in modelling capability, but in the context of cold region hydrology, major challenges remain around processes such as blowing snow redistribution and sublimation, frozen soil infiltration and permafrost degradation, glacier melt and dynamics. Below the MESH modelling platform is introduced, and then recent model developments in these areas, as well as the spatial disaggregation of forcing data are described. Recent enhancements of model capability are demonstrated, including the representation of prairie landscapes and water management, and the opportunities offered by recent advances in modelling science, specifically associated with new tools for sensitivity analysis of large scale, physically-based models, and remote sensing data.

3 | THE MESH MODELLING PLATFORM

The complex interdependency of geospatial information, observations and models requires systematic approaches for large scale hydrological modelling. In Canada, this effort began in the 1990s (Soulis et al., 2000) with the Mackenzie Global Energy and Water Experiment (GEWEX) program and the coupling of land surface models (LSMs) developed for climate models to hydrological models (Pietroniro et al., 2001; Pietroniro & Soulis, 2003). In parallel, research was underway to improve hydrological fluxes in numerical weather prediction models through the coupling of atmospheric and hydrological models (Benoit et al., 2000). To accelerate and operationalize model development, Environment Canada (now called ECCC) developed a community environmental modelling system, Modélisation Environmentale Communautaire (MEC) (Pellerin et al., 2004), which allowed different surface models to be evaluated within the same modelling framework. The operational version of MEC at the time included three land-surface schemes (LSSs): a simple force-restore scheme; a version of the interaction soil-biosphere-atmosphere scheme (ISBA; Bélair et al., 2003, b), which has since evolved to the Soil-Vegetation-Snow (SVS) scheme (Husain et al., 2016); and the Canadian Land Surface Scheme (CLASS) (Verseghy, 2000).

In the IP3 Cold Regions Hydrology Network (https://gwfnet.net/sites/ip3/), MESH was developed (Pietroniro et al., 2007) as a modular framework for MEC that included a hydrological hillslope model, where sloped surfaces generate routed overland runoff and lateral interflow (Soulis et al., 2000, 2011), and a hydrological routing scheme (from the WATFLOOD hydrological model, Kouwen, 1988). To represent subgrid variability, CLASS was run in MESH for different tiles on each grid cell, based on hydrological response units (HRUs). MESH combines HRUs into grouped response units (GRUs) (Kouwen et al., 1993) that use common parameter values to represent landscape classes that extend beyond each grid cell, thus incorporating the necessary physics while reducing the computational and parameterization burden. As with all land-surface models, network topology, land-use and soils information, input parameters and forcing data are pre-processed to match the delineated domain, and a spin-up period is used for the initialization of state-variables. Grid cells can be regularly spaced meshes (grid-based) or irregularly shaped sub-basins (vector-based).

Different LSSs, such as CLASS and SVS, can be activated in MESH. Both schemes contain detailed physics to represent vegetated canopies, snow covered areas and barren lands, however CLASS is also able to simulate bare rock, frozen soils, permafrost, intercepted snow, blowing snow and glaciers and contains parameterizations to represent peatland soils. This makes CLASS more appropriate for cold

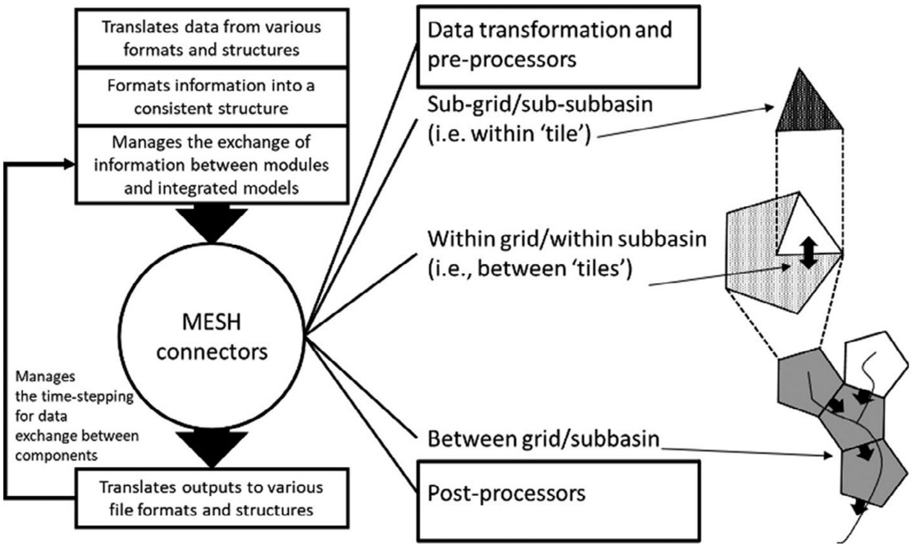

FIGURE 2 The MESH modelling framework allows for user flexibility in river basin discretization, ranging from regular grid cells to irregular sub-basins, provided each cell or sub-basin contains a stream. Each grid cell or sub-basin (referred to as grid cells forthwith) has distinctive atmospheric forcings as its mass and energy inputs and outputs distinctive streamflow that is routed within the river basin. Sub-grid cell variability is conceptualized via Tiles, which have distinctive sets of parameters and state variables and may have distinctive mass exchanges (e.g., blowing snow redistribution amongst Tiles) within the grid cell. Tiles with identical parameter sets in different grid cells can be grouped and referred to as Grouped Response Units (GRU). Parameterization of GRUs is treated consistently across the river basin to limit the degrees of freedom in parameter values

region applications and development. In CLASS, the soil profile is configurable as a user-provided input of at least three layers that typically increase in thickness with depth. Soil properties are derived from pedotransfer functions, and the permeable depth of the column is permitted to vary by GRU or grid cell. Hillslopes are derived from digital elevation properties and can be assigned on a GRU or grid cell basis.

The physical basis of MESH requires that simulations be run using a sub-daily time-step. Within a time-step, runoff from the LSS can contribute to lower zone storage and then to baseflow routing or directly to surface river channel and reservoir routing. Network topology defines domain interconnections and flow routing. Reservoirs and lakes can be represented using various parameterizations or lookup tables, and water diversions are permitted to bypass the natural flow directions. Two-way coupling of the land surface and routing schemes allows water to be redistributed, to satisfy irrigation demands driven by soil or atmospheric conditions.

A decade of investment from ECCC and its academic partners has resulted in substantial technical and scientific advancements in MESH, https://research-groups.usask.ca/hydrology/modelling/mesh.php. These improvements have converted MESH from a simple land-surface model into a robust modelling framework that is freely available, encourages community development, and can be run on many different computing platforms, from personal computers to supercomputers optimized for parallel computations (Figure 2). The modular framework contains multiple hydrological land surface schemes, and supports multiple modes for basin representation, including legacy grid-based, single column, and vector-based configurations. This allows maximum flexibility for scientific development while allowing for simple translation into operational settings. The MESH system can scale from smaller research basins to large river basins and has been successfully used by researchers to incorporate advances in the numerical representation of natural processes, which has informed ECCC's operational systems. It has also been used as an operational tool to produce hydrological forecasts for Canadian provinces and territories. The framework supports data exchange in multiple file formats and integration within Canada's Flood Early Warning System (FEWS). The model structure is supported through open-source approaches and is compatible with current industry standards such as NetCDF file formats, making development and visualization much more efficient. The code is available on a GitHub repository (https://github.com/MESH-Model) and details around model development, training, benchmarking and code reviews, are maintained through community Wikis. The code is maintained by ECCC and is available through the Wiki Page, https://wiki.usask.ca/display/MESH/; individuals can contribute to the code base by coordinating with ECCC. Slack and Wiki are used to share code ideas and a development team, which includes government scientists, engineers and university teams, meets monthly.

4 | RECENT SCIENTIFIC DEVELOPMENTS IN MESH

4.1 | Improved process representation

Key process innovations in MESH have focused on the scientific challenges of cold region modelling and have been based on detailed process research:

4.1.1 | Blowing snow transport and sublimation

Blowing snow redistribution and sublimation are important processes in open, cold regions (e.g., Pomeroy & Li, 2000), but are rarely included in other large scale hydrological models or LSSs. MESH's CLASS routines for coupled snowpack energy and mass balance and snow interception processes have been coupled to the Prairie Blowing Snow Model (PBSM, Pomeroy et al., 1993; Pomeroy & Li, 2000). PBSM was initially developed for the Canadian Prairies, characterized by relatively flat terrain and homogeneous surface roughness, and calculates blowing snow transport and sublimation rates for steady-state conditions. However, it has been shown to be suitable, with modifications, for modelling snow covers in prairie, arctic and alpine environments. Adjustments have been made for limited fetch, variable vegetation heights and wind flow over complex terrain (Essery et al., 1999; Fang et al., 2013; Fang & Pomeroy, 2009; MacDonald et al., 2010; Pomeroy & Gray, 1995). Snow transport is calculated as the sum of saltation (Pomeroy & Gray, 1990) and turbulent suspended mass fluxes (Pomeroy & Male, 1992), coupled with a blowing snow sublimation calculation for a single column control volume that extends from the snowpack surface to the top of the surface boundary layer (Pomeroy et al., 1993). Within a MESH grid cell, snow is transported from windswept GRUs to downwind GRUs as specified by the modeller and hence constitutes a redistribution of snow. This GRU to GRU blowing snow flow innovation permits large scale simulation of blowing snow redistribution within a MESH grid cell and is scalable to continental regions.

4.1.2 | Frozen ground infiltration and thermodynamics

Frozen soil is another important feature of cold regions and a major control on hydrological response. Infiltration and water movement in partially frozen soils require simulation of both water and energy balances in soils, and the profile distribution of liquid and solid water contents. MESH allows the modeller to specify the number of soil layers, with a minimum of three. The thermal and hydraulic properties of each soil layer differ for various subsurface material types. Soil thermal conductivities are used, based on Côté and Konrad (2005), to calculate heat fluxes between soil layers, and at the soil-atmosphere and soil-snow interfaces, and thus determine the non-radiative fluxes. A finite-difference scheme for the one-dimensional heat conservation equation is applied to each soil layer. Soil water suction and hydraulic conductivities are calculated from the widely-applied Clapp and Hornberger (1978) relationships. Infiltration into the topsoil layer is estimated using a Green-Ampt (Rawls et al., 1983) formulation. By default, soil hydraulic properties are determined from soil texture using the Cosby et al. (1984) pedotransfer functions (Ireson et al., 2022). Soil thermal properties for each layer depend on the liquid and frozen water contents in addition to the soil texture and organic content.

To account for the controls on infiltration in frozen soil, MESH uses the Zhao and Gray (1999) algorithm, a general parametric expression derived for prairie and boreal forest environments. This relates infiltration to total soil saturation (liquid + frozen moisture content) and temperature at the beginning of snowmelt, soil surface saturation during melt, and the infiltration opportunity time. Infiltration calculations are grouped into three categories, *Restricted*—infiltration is completely restricted due to impermeable surface conditions such as ice lens formation, *Limited*—capillary flow predominates and infiltration is primarily controlled by soil physical properties, and *Unlimited*—gravity flow predominates and water infiltrates.

4.1.3 | Permafrost initialization and dynamics

Permafrost, defined as perennially cryotic ground for at least two consecutive years (International Permafrost Association, 1998), presents great challenges for hydrological modelling. Permafrost thaw has been widely observed in recent decades, and has important implications globally, with increased methane release to the atmosphere, and locally, with vulnerability of man-made structures (Dobinski, 2011; Hjort et al., 2018; Walvoord & Kurylyk, 2016; Woo, 2012). Observed effects include changing hydrological connectivity, landscape collapse, and vegetation change (DeBeer et al., 2016; McGuire et al., 2018; Pan et al., 2016); current climate model projections agree that this will continue (Burke et al., 2020; Meredith et al., 2019).

MESH couples both water and energy balances in soils and allows for various depth and layering configurations that allow simulation of permafrost dynamics. Major improvements have been made to solve the complex problem of permafrost initialization and provide additional insights into permafrost dynamics. Firstly, the insulation of frozen soil by snow cover and soil organic matter has been shown to be an important regulator of atmospheric effects on permafrost thermal and hydraulic regimes (Dobinski, 2011). Hence the model has been enhanced with an explicit organic soil parameterization (Letts et al., 2000), representing complex vegetation dynamics (Melton et al., 2019), and employing surficial moss as a topsoil layer (Wu et al., 2016).

The second group of enhancements relates to configuring and initializing MESH to simulate permafrost evolution. Typical LSSs use shallow soil profiles, which fail to represent the evolution of the coupled soil heat and moisture states/storage. Allowing a deeper soil configuration, coupled with the inclusion of a geothermal flux at the bottom boundary of the soil/rock column (Verseghy, 2012) facilitates simulation of freeze/thaw cycles and subsurface heat storage (Alexeev et al., 2007; Nicolsky et al., 2007). However, the long thermal memory of the system requires substantial spin-up to set the initial conditions (Sapriza-Azuri et al., 2018) as observational information is not usually available.

Elshamy et al. (2020) devised a novel approach for model initialization and parameterization, based on three long-term observational sites in the Mackenzie River Basin (MRB) (Figure 1), encompassing different permafrost classes. An upscaling methodology was proposed in

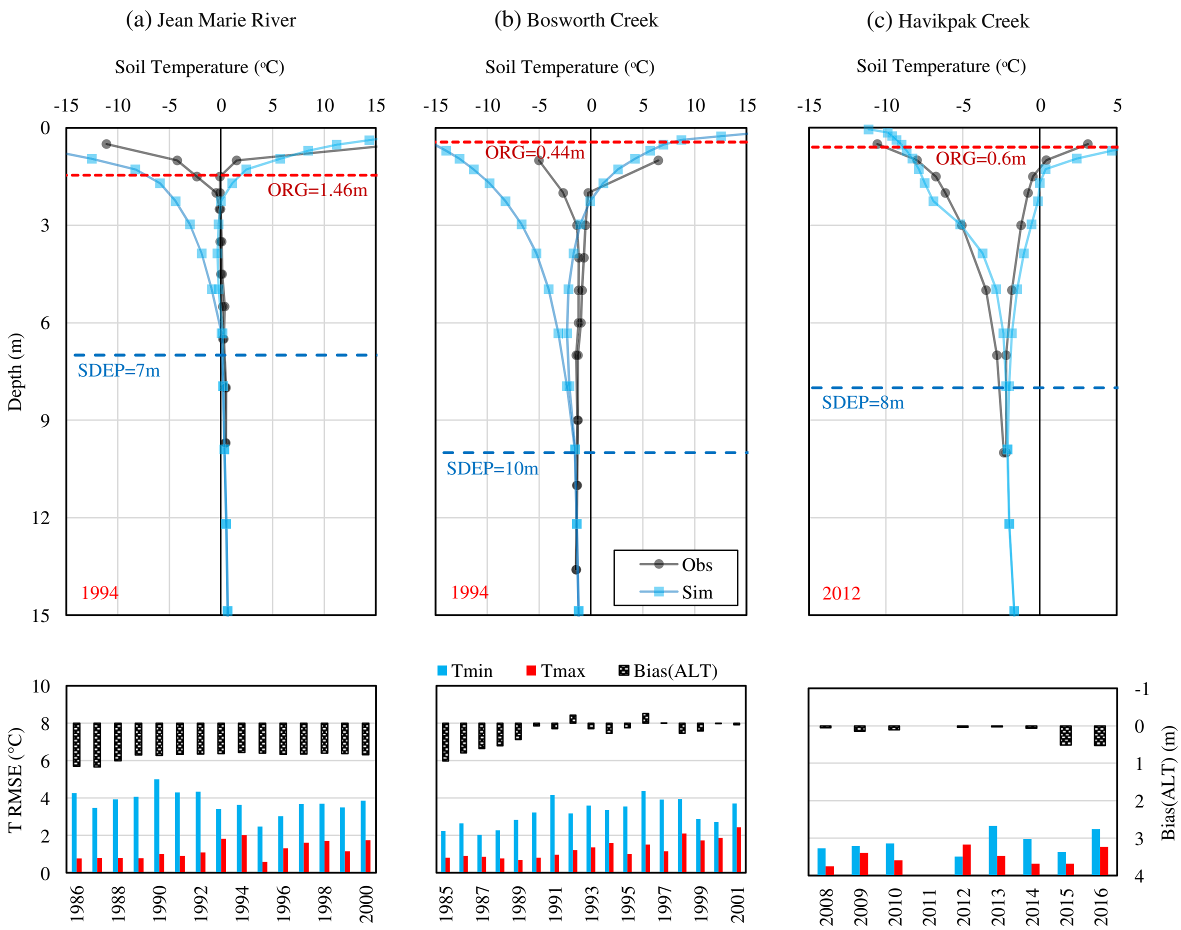

FIGURE 3 Performance of MESH in simulating permafrost at three sites in the MRB, top panel shows the simulated annual temperature envelopes for the top 15 m of the profile compared to observations for a selected year at each site; lower panel shows, for each site, the annual RMSE for the temperature envelopes (Tmax and Tmin, calculated along the depth axis, interpolated at the measurement positions) and the bias in simulating the active layer thickness in each year. Years vary by site depending on availability of observations. Site locations are shown in Figure 1

which insights from small-scale simulations were transferred to large domains. This methodology resulted in a 50 m deep soil profile across the domain, accompanied by 50–100-year spin-up cycles. Figure 3 highlights the performance of MESH in simulating permafrost for the three sites, after Elshamy et al. (2020). Abdelhamed et al. (2022) have further highlighted the role of initial moisture content, especially ice, and the choice of the spin-up year meteorology on model initialization and subsequent simulation. This research has highlighted the sensitivity of hydrological response to permafrost simulations, but nevertheless, the need to initialize what is a transient permafrost state with a long (decadal or more) memory, limited ground observations and highly uncertain historical forcing data remains a major challenge.

4.1.4 | Glacier processes

Glaciers are a distinct feature of cold region landscapes and hydrology, and support late summer flows in regions fed by mountain headwaters. However, glaciers have been rapidly decreasing in volume and areal extent in many regions, due to global warming (DeBeer et al., 2020; IPCC, 2019). CLASS includes a glacier module that simulates the key processes for capturing glacier energetics and melt rates, including the mass balance of snow/ice melt, ponding, runoff, and conversion of snow to ice. As glacier ice has a lower albedo than seasonal snowpacks, the net incoming shortwave radiation of a melting glacier can be two to three times that of a melting snowpack. MESH parameters include glacier albedo and snow-to-ice conversion thresholds based on snow water equivalent and snow density, with recommended values consistent with measurements in the Canadian Rockies (Pradhananga & Pomeroy, 2022). The glacier module calculates glacier mass balance and depth without iceflow by representing glaciers as a GRU with static areal extent.

The performance of the glacier module was assessed by comparing simulated annual mass balances with observations of Peyto Glacier in the Canadian Rockies (Pradhananga et al., 2021) reported to the World Glacier Monitoring Service (WGMS; https://wgms.ch/) (Figure 4). This confirmed the suitability of the parameterization and is believed to be the first reported comparison of the annual glacier mass balance of a hydrological land surface model to observations and

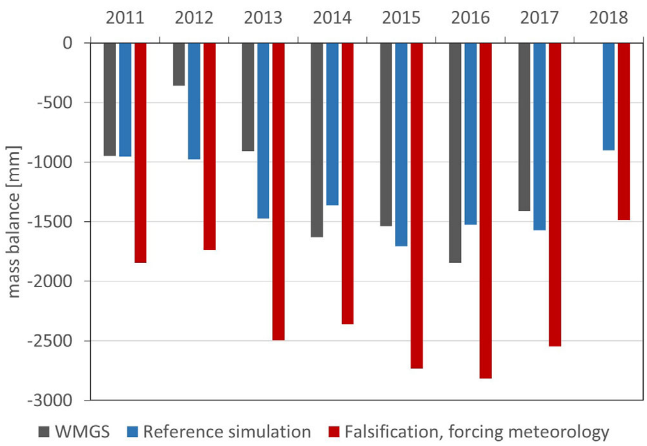

FIGURE 4 Comparison of measured mass balance of Peyto glacier submitted to the WGMS to a reference MESH simulation of the mass balance as configured with Mountain MESH (forcing meteorology accounts for slope, aspect, elevation lapse of P, T, RH and wind speed acceleration over complex terrain) with PBSM. Falsification turns off Mountain MESH changes to forcing meteorology

so confirms that glacier change can be realistically represented in large river basin hydrological models.

4.1.5 | Spatial discretization and mountain hydrometeorology

Mountain slope and aspect can be important controls on incoming shortwave radiation for snowmelt and evapotranspiration. MESH has various discretization options to address this: a GRU can be discretized based on land-cover types, slope, aspect, elevation, soil and other spatial features of hydrological importance. In mountains, the combination of land cover, slope-aspect and elevation can be used as together they strongly control snow accumulation and energetics (Figure 5).

Beyond GRU discretization, the capability to disaggregate the meteorological forcing fields inside the model grid has been added, which current LSMs lack. This configuration, 'Mountain MESH', includes a module to adjust forcing data for elevation and slope. Air temperature from a lower-resolution numerical weather prediction model can be re-distributed to GRUs at different elevations using a locally-derived lapse rate. Air pressure is adjusted from the original low-resolution fields using the corrected temperature and other constants. Specific humidity is a nonlinear function of elevation and is corrected based on actual vapour and surface pressure fields, based on Buck (1981). The incoming shortwave radiation is used to correct the theoretical radiation on sloped surfaces for cloud cover, by comparing the low-resolution forcing field with the theoretical flat surface radiation estimate (Garnier & Ohmura, 1968, 1970). Incoming longwave radiation is corrected for elevation using lapse rates developed from the high-resolution forcings and elevation using Brutsaert (1975). Precipitation depth and phase are corrected from the elevation differences between the high-resolution GRUs and low-resolution forcing fields using the Elevation Range with Maximum elevation Method (ERMM) (Tesfa et al., 2020). Wind speed is corrected for topography following the simple formulations of Liston and Elder (2006). The impact of these modelling features on glacier mass balance is shown in Figure 4 and for mountain snow simulations in Section 4.2.1. This has provided a mountain hydrological modelling capability that exceeds that of other large scale models in that it includes a full downscaling of forcing meteorology and then tracking of mass and energy balances in mountain headwater regions. Capturing the hydro-thermodynamics of these regions is particularly important as mountain headwaters are the source of many global rivers that supply water for extensive, drier downstream regions.

4.2 | Evaluation of model performance

Having described various process improvements, we next consider model performance for various landscape types.

4.2.1 | Mountain and snow hydrology evaluation

Cold region hydrological processes are strongly influenced by precipitation, blowing snow redistribution, snow interception by canopy, sublimation, and the exchange of radiative and turbulent fluxes. Snow process modelling has been evaluated in numerous studies (e.g., Davison et al., 2006; Dornes, Pomeroy, et al., 2008; Dornes, Tolson, et al., 2008; Pomeroy et al., 1998; Verseghy et al., 2000) and as part of various snow model intercomparison projects (e.g., Brown et al., 2006; Krinner et al., 2018; Rutter et al., 2009). Recent MESH/CLASS revisions include an updated fresh snow density parameterization (Brown et al., 2006), a revised snow ageing algorithm (Bartlett et al., 2006; Brown et al., 2006), a new parameterization for snow canopy interception and unloading (Bartlett et al., 2006) after Hedstrom and Pomeroy (1998), as well as an adjusted formulation for the albedo of snow-covered forest canopies (Bartlett & Verseghy, 2015). Options for precipitation phase and the partitioning of precipitation into rain or snow include empirical formulations based on air temperature (e.g., Bartlett et al., 2006; Brown et al., 2006) and the hydrometeor temperature, which can be accurately estimated as a function of the psychrometric energy balance (Harder & Pomeroy, 2013).

An updated evaluation of MESH, based on observations at different alpine research sites in the Canadian Rockies is reported by Fayad and Pomeroy (n.d.) where the model was run in single column mode for different alpine sites at the Marmot Creek Research Basin (e.g., alpine ridges, alpine forests and clear cuts, and montane sites), forced by hourly meteorological observations. Shortwave and longwave irradiance were adjusted for slopes, and air temperature, humidity, pressure, and precipitation for elevation. Overall, the model showed good performance in capturing snow accumulation, snowmelt

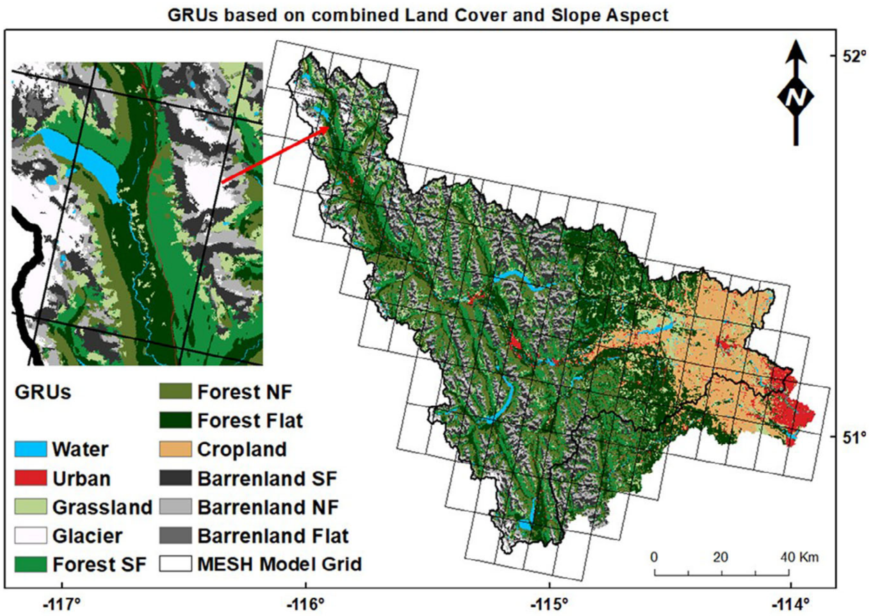

FIGURE 5 GRU discretization (shown by colour shading) using combined land cover and slope aspect for mountain MESH for Bow River Basin above Calgary, Alberta, Canada

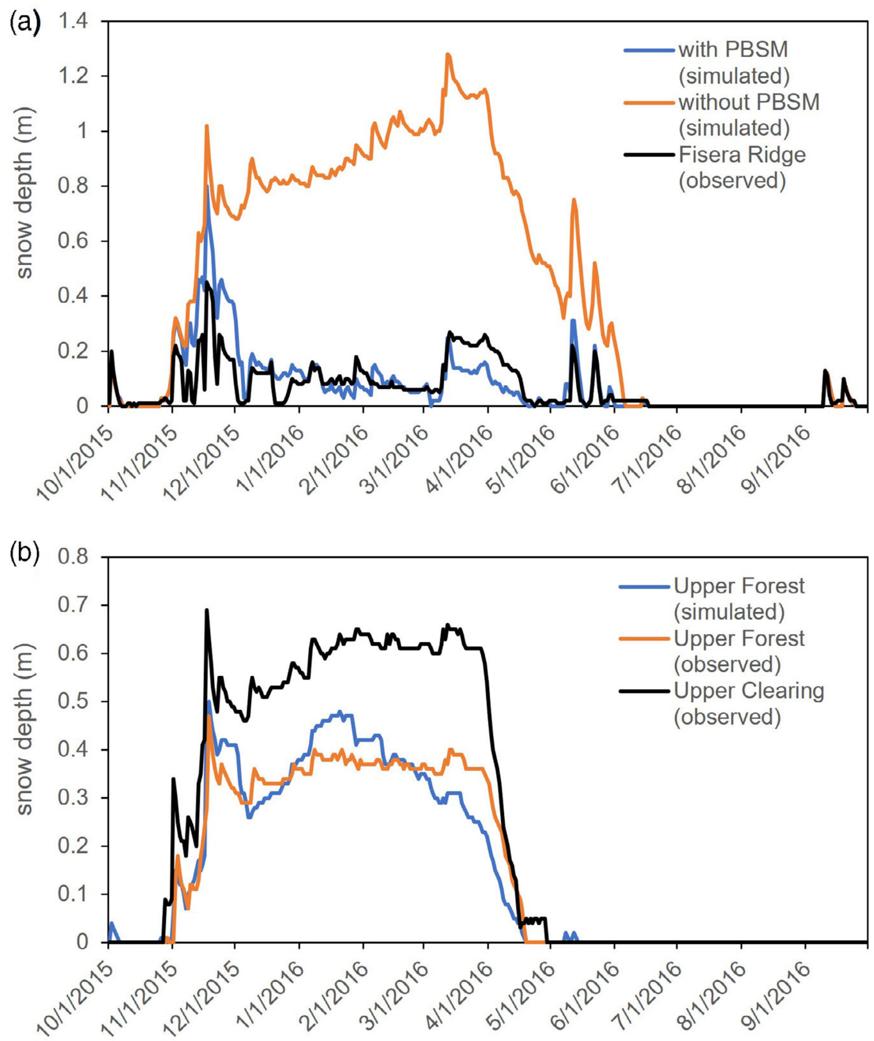

FIGURE 6 (a) Simulated and observed snow depth at Fisera Ridge (2325 m) from Marmot Creek Research Basin (Fang et al., 2019) showing model improvements when using blowing snow sub-routine PBSM after Pomeroy and Li (2000) compared to running the model without accounting for blowing snow. (b) Observed and simulated snow depth under forest canopy at the Upper Forest (1848 m) from Marmot Creek Research Basin compared to observed snow in the Upper Clearing (1845 m)

onset, and ablation rates. On wind-blown, high alpine ridges, the model could simulate snow water equivalent (SWE) well when its blowing snow algorithms were used (Figure 6a). Simulations of snow accumulation under forest canopies were acceptable, suggesting that snow interception and sub-canopy snow energetics were well simulated (Figure 6b). In contrast, the use of conventional driving meteorology, not accounting for terrain impacts on radiative forcing or elevational impacts on precipitation and temperature, caused large errors in SWE and the timing of snowcover disappearance.

4.2.2 | Boreal Forest hydrology

The Boreal Forest (BF) covers 60% of Canada's land surface, and comprises forested uplands, wetlands, lakes and grasslands (Brandt et al., 2013). MESH has had a particular focus on the BF since the early 1990s, when global scale model runs produced positive temperature biases over the BF in Canada and Siberia, attributed to flaws in vegetation characterization. The BOREAS experiments in the southern boreal forest in Saskatchewan and Manitoba were initiated to address some of the model deficiencies, and many field sites continue to this day (now known as the Boreal Ecosystem Research and Monitoring Sites [BERMS]; Barr et al., 2012; Ireson et al., 2015) and support MESH improvement.

Initial simulations of BF evapotranspiration applied CLASS to the BERMS sites (1994–1996) (Snelgrove, 2002). Evapotranspiration was largely overestimated but could be reduced by allowing for lateral runoff and accounting for mild slopes. Bartlett et al. (2003) further improved the soil and vegetation parameterization using BERMS data. Notably, canopy conductance was reduced (compared to temperate forests) which also resulted in improvements in evapotranspiration, though it was still overestimated at the Old Jack Pine stand. Davison et al. (2016) applied MESH to the Whitegull Creek watershed, Saskatchewan (Figure 1), where two of the BERMS sites are located, and showed that by calibrating to streamflow, evaporation estimates could be improved. However, evapotranspiration at the Old Jack Pine site remained over-estimated. Ireson et al. (2022) conducted single column model runs with CLASS at three BERMS sites. They calibrated the model to soil moisture observations and showed that the pedotransfer functions in CLASS restrict the ability of the model to simulate soil moisture. They suggested that the ability of CLASS/MESH to simulate evapotranspiration could be improved by modifying the soil hydraulic properties directly (not using pedotransfer functions), and by focusing on infiltration and plant water uptake during the melt period.

Letts et al. (2000) introduced a CLASS parameterization for peatlands, which comprise 12% of the BF and have distinct hydraulic and thermal properties. An equivalent water table depth was introduced based on water content, and new soil parameters were defined, which led to simulation improvements (for a fen in northern Quebec and a bog in north-central Minnesota). However, they noted that further improvement would require groundwater inputs and hillslope hydrology. A conceptual model of BF hydrology (Ireson et al., 2015) reinforced the importance of lateral flow processes and current work has demonstrated that wetland modelling requires improved representation of groundwater and surface runoff inputs from adjacent uplands.

Moving from the single column to small research basin scale, Snelgrove (2002) used a soil moisture scheme (after Soulis et al., 2000), which introduced lateral outputs (surface runoff and interflow) to be routed from the GRU level to MESH grid cells. Streamflow in Whitegull Creek was overestimated during the snowmelt period, which suggested that more infiltration into frozen soils is needed. The snow accumulation algorithm in CLASS was subsequently improved by allowing for mixed precipitation, improvements in the snow density and canopy unloading (Bartlett et al., 2006). Davison et al. (2016) applied MESH in the same watershed as Snelgrove, and found that with calibration, the model was generally able to simulate streamflow well, including during snowmelt. One exception was the year 2011 when the model failed to simulate a large flood peak in the snowmelt period. Ganji et al. (2017) used a modified version of CLASS with WATFLOOD to simulate streamflow in a series of basins in the BF in Quebec and found that streamflow could be improved by modifying frozen-soil infiltration. MESH implementation in the BF region could be further improved for very wet conditions, and in the partitioning of snowmelt between infiltration and runoff.

4.2.3 | Prairie hydrology connectivity

The Canadian Prairies are nationally important areas of agricultural production, characterized by a distinctive landscape that contains millions of small depressions of glacial origin, called prairie potholes. Similar landscapes are found in the northern US Great Plains. The wetlands that form in these depressions are hydrologically significant due to their surface storage capacity and dynamic connectivity (Shook & Pomeroy, 2011; Van der Kamp & Hayashi, 2009). Under normal conditions most of these wetlands drain episodically to a terminal wetland. In such cases, the basin is internally drained and considered closed as part of the non-contributing area for runoff generation to the larger river systems in which they are located (Fang et al., 2010; Leibowitz & Vining, 2003). However, this connectivity is dynamic, leading to variable contributions to major river systems, particularly under extreme flood events (Ahmed et al., 2021). This has long presented a major challenge to hydrological models.

In recent years, airborne LiDAR and high-resolution satellite data have enabled detailed mapping of pothole topography, and high-resolution simulation methods have been used to quantify the dynamic connectivity and the associated, sometimes hysteretic, storage-discharge relationships. Early modelling of the variably connected fractions of Prairie basins by Shaw (2009), then extended to a larger number of ponds (Shaw et al., 2012, 2013), led to a generalized approach of characteristic curves for pothole complexes that related overall volume to the contributing area, and was the first to note the hysteretic behaviour of these curves. Shook and Pomeroy (2011) and Shook et al. (2013, 2021) extended the work to larger domains, using

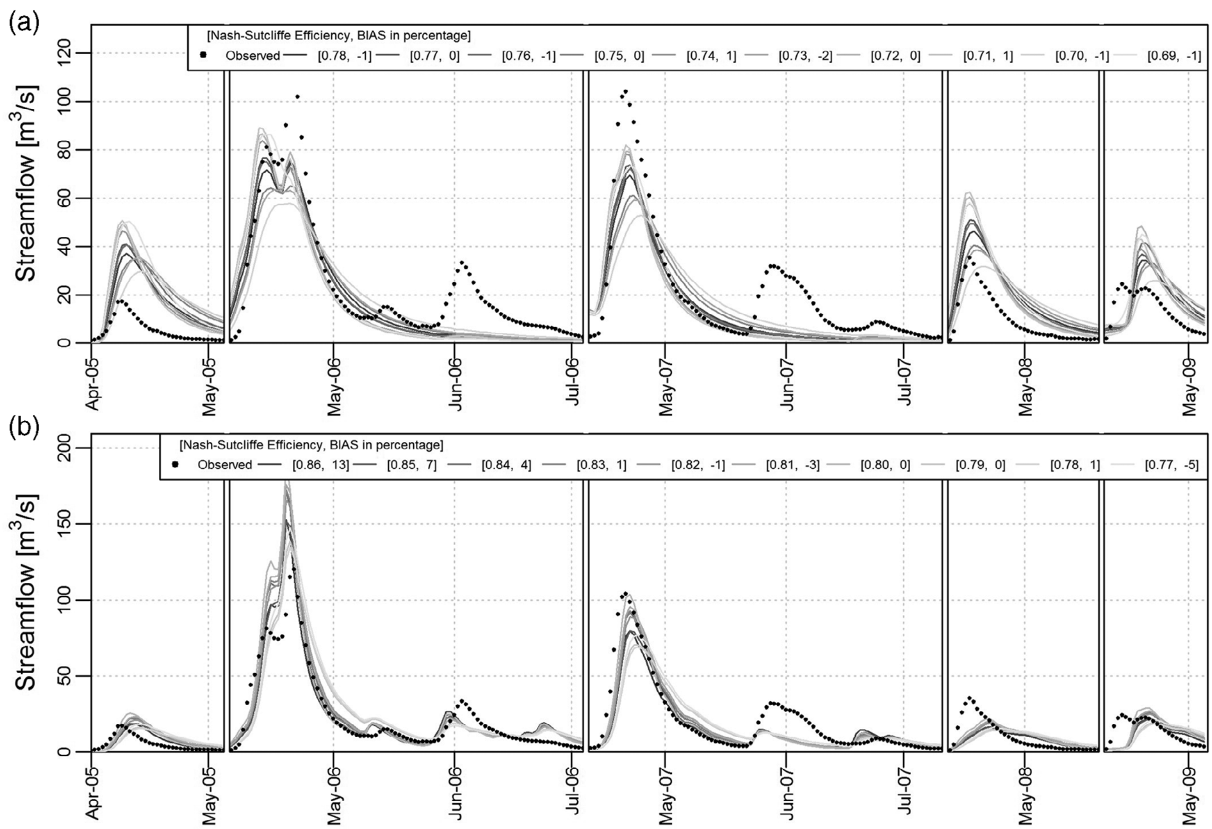

FIGURE 7 Best 10 stream flow simulations for using MESH without (a) and with (b) the PDMROF algorithm for the Assiniboine River at Sturgis (gauge 05MC001). Reproduced from Mekonnen et al. (2014) with the permission of Elsevier

statistical approaches. Despite these advances, the logistic constraints associated with the landscape complexity have required simplified hydrological simulations in MESH, and there remains a major challenge to model the hydrology of these systems at both local and regional scales. Explicit solutions for small domains have been proposed and tested (Shook et al., 2013, 2021), and coupled directly to MESH (Ahmed et al., 2021).

A conceptual approach to deal with the large-scale simulations was developed for MESH based on the Probability Distribution Model based RunOFf generation (PDMROF) algorithm (Mekonnen et al., 2014), derived from the PDM concept of Moore (2007). This uses the Pareto distribution to represent dynamic contributing area in a lumped fashion as a function of basin storage. PDM concepts have been applied in the VIC model (Wood et al., 1992) and in several land surface schemes used in weather and climate modelling (Blyth, 2001; Dümenil & Todini, 1992). However, this was the first attempt to represent the surface water connectivity that results from the 'fill and spill' of prairie potholes within a coupled hydrologic land-surface scheme. As shown in Figure 7, PDMROF improved the simulation of streamflow in the Assiniboine River in the prairie agricultural region of Saskatchewan (see Figure 1 for the location) and captured the dynamic nature of contributing areas in an effective and parsimonious manner. The model performed well for high flows, suggesting it could be useful for simulating flood conditions—a particular concern in the prairies of Canada and the United States following widespread flooding in 2011.

A limitation of the first implementation of PDMROF is that it does not allow shallow subsurface flow to contribute water from local hillslopes that often surround prairie potholes. Hossain (2017) coupled PDMROF with shallow subsurface hillslope flow (after Soulis et al., 2000) to improve flow-pathway simulations. Recently, explicit solution approaches to pothole modelling were proposed by Ahmed et al. (2020) and coupled to MESH (Ahmed et al., 2021) for small prairie basins. This captured the spatial and temporal dynamics of the surface water storage in the prairies to address the limitations of the PDMROF algorithm, capturing the hysteretic behaviour of the storage-discharge and the storage-contributing area relationships.

4.3 | Modelling reservoirs and irrigation

Most river basins have been significantly altered by land and water management and other human interventions, including dams, diversions and abstraction of water from surface and groundwater resources (Hanasaki et al., 2006; Nazemi and Wheater, 2015a,2015b; Pokhrel et al., 2012). To address some of this, Yassin et al. (2019) developed reservoir and irrigation modules within the MESH modelling system.

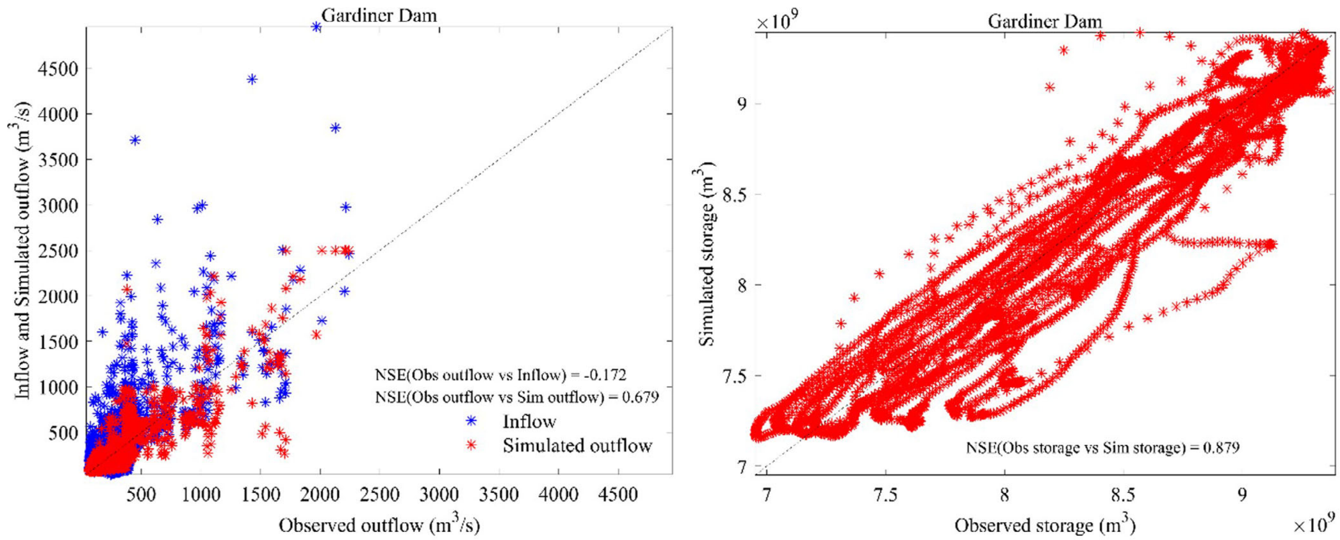

FIGURE 8 Improvements in reservoir simulation for the Gardiner Dam using the DZTR algorithm

The dynamically zoned target release (DZTR) reservoir operation model was introduced to add dynamic characterization of reservoir storage zones and releases using observed reservoir inflow, storage, and discharge data. Water release decisions are made at each time step via piece-wise linear and monotonic functions of reservoir storage and inflows, parameterized to accommodate varying degrees of local data availability and computational resources. Yassin et al. (2019) showed that the model outperformed existing widely used methods and simulated more realistic reservoir storage and outflow at multiple dams across the globe, and subsequently improved the fidelity of large-scale modelling when tested in the highly regulated Saskatchewan River Basin (SaskRB). Figure 8 shows results for the Saskatchewan river's largest dam as an example of the reservoir model performance.

To capture the combined effect of reservoir flow regulation and irrigation demand and supply, a soil moisture deficit-based irrigation demand model was integrated alongside a flow withdrawal model. A unique feature of this model is that it customizes the demand calculation to mimic the irrigation management performed in local-scale irrigation districts. The demand from each irrigation area can be aggregated into districts, and water supplied locally or from a defined abstraction point in the river channel. Implementation over the SaskRB showed irrigation significantly changes the surface water and energy balance over the irrigated areas. Figure 9 shows the large changes in annual evapotranspiration due to irrigation.

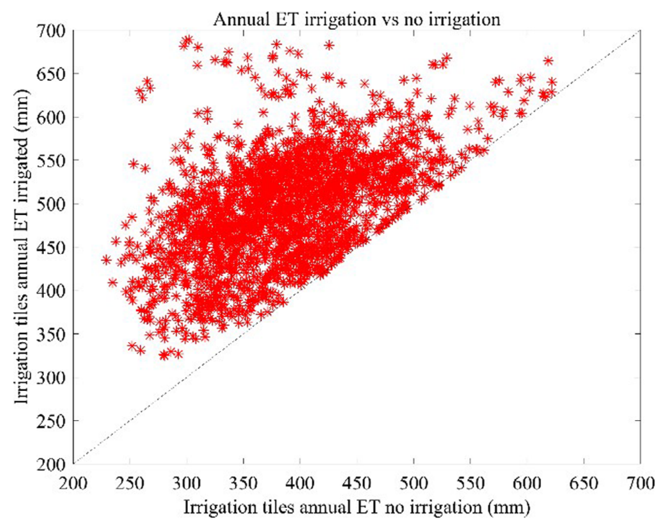

FIGURE 9 Simulated changes in actual evapotranspiration resulting from irrigation in the South Saskatchewan Basins

4.4 | Model parameterization and sensitivity analysis

MESH has a complex structure with many parameters; understanding how different parameters influence model behaviour is key for MESH development and application. Sensitivity analysis (SA), the study of how model outputs are related to, and influenced by, its inputs (Razavi et al., 2021), has been integral to the recent development of MESH, facilitated via the Variogram Analysis of Response Surfaces (VARS) framework (Razavi et al., 2019; Razavi & Gupta, 2016a).

SA has been conducted on MESH across various hydroclimatic conditions and scales in Canada, including Boreal forests (Razavi & Gupta, 2016b), prairies (Haghnegahdar et al., 2017; Yassin et al., 2017), and more typical hillslope landscapes (Haghnegahdar et al., 2017; Haghnegahdar & Razavi, 2017). The most influential parameters controlling high flows, low flows, total flow volume and soil moisture have been documented. To address the high dimensionality in the MESH parameter space, Sheikholeslami et al. (2019) devised a method to group parameters, from strongly influential to uninfluential, in terms of their importance in representing streamflow. Overall, parameters controlling soil water storage capacity, and particularly permafrost active layer depth, have been highly influential for simulating streamflow and soil moisture. Parameters controlling river routing such as channel roughness strongly influence streamflow, particularly high flow values and their timing. Soil moisture is largely influenced by parameters controlling soil and vegetation properties, especially during low flow periods. Many MESH parameters are physically identifiable to some extent, permitting their identification, or their plausible ranges, from DEMs, soil surveys, satellite vegetation mapping, hydrometry analysis in GIS and observed channel characteristics. MESH implementation on the SaskRB has shown acceptable performance without parameter calibration, suggesting the model can perform well when applied to ungauged basins where calibration is not possible (Yassin et al., n.d.).

4.5 | Remote sensing data for improved model fidelity

Space-based Earth observations can provide insights into Earth surface process interactions and transitions (Tapley et al., 2019). For hydrological applications, an important concern is their effectiveness in improving model process understanding and simulation. Several studies have explored the utility of Gravity Recovery and Climate Experiment (GRACE) observations. Yirdaw et al. (2009) found general agreement between model simulations of terrestrial water storage and satellite retrievals for the Mackenzie Basin. Yassin et al. (2017) demonstrated the benefit of combining GRACE and streamflow data for model parameter identification for the SaskRB using multi-criteria sensitivity analysis and optimization. Results showed that streamflow was dominantly controlled by routing parameters, while soil parameters strongly influenced storage variability. Multi-criteria optimization with both streamflow and GRACE observations gave improved parameter identification and storage and streamflow simulations, demonstrating the benefits of GRACE data at these large scales, allowing the use of the model's internal states in model fitting in addition to streamflow. More recently, Bahrami et al. (2021) integrated the Ensemble Kalman Smoother (EnKS, Evensen & Van Leeuwen, 2000) for data assimilation, and showed improved monthly SWE estimates at basin and grid scales for the Liard basin. GRACE data assimilation in streamflow simulations was evaluated against observations from multiple river gauges, where it improved high flows' simulations during the snowmelt season. Thus, GRACE data can improve regional estimates of SWE, streamflow, hydrological fluxes and terrestrial water storage compartments.

Soil Moisture and Ocean Salinity (SMOS) soil moisture retrievals have also been used to support MESH application. Xu et al. (2015) applied a one-dimensional Ensemble Kalman Filter (1D-EnKF) using SMOS data over the Great Lakes. The methodology improved soil moisture estimation for both surface soil and the root zone over crop-dominated areas. Overall, the use of satellite-based observations within MESH has been shown to improve parameter identifiability and model fidelity and offers considerable promise for further development.

5 | EXPANDED SCOPE OF THE MESH MODELLING SYSTEM

MESH has potential to support a wide range of integrated modelling applications; current research includes water resource systems analysis and vulnerability assessment, hydro-economic modelling and carbon budget modelling, including dynamic vegetation. Given its strengths in cold region processes, below we highlight recent developments for river ice modelling, water quality and habitat suitability.

5.1 | MESH extension to river ice and water quality

More than one-third of the Earth's landmass is drained by rivers that experience seasonal river ice, and 66% of Northern Hemisphere river length is ice-covered in March (Yang et al., 2020). River ice is thus an integral component of the hydrologic and hydraulic regimes of rivers in cold regions and regulates hydrologic, hydraulic, geomorphic, biological and chemical processes (Beltaos & Prowse, 2009; Prowse, 2001). While it provides important socio-economic and ecological benefits (Das et al., 2018), ice-jams and associated flood events result in human casualties, damage infrastructure, impair navigation and hydroelectric production, and impact ecology and water quality (Rokaya et al., 2018a; Lindenschmidt, 2020).

Comprehensive assessment of river flows and ice in these regions is only possible through integrated hydrological and hydraulic modelling. The river basin model (RBM), a semi-Lagrangian, one dimensional, process-based stream water temperature model (Yearsley, 2012) has been combined with MESH. MESH-RBM can be used to simulate and forecast ice-cover durations (Morales-Marín et al., 2019b), and has also been applied in operational forecasting of river ice breakup (Rokaya et al., 2020a; Rokaya et al., 2020b). The model provides a practical tool for ice-jam flood forecasting and warning, and simulates breakup progression for the entire catchment, providing an advantage over existing site-specific prediction methods. Figure 10 illustrates catchment scale forecasting of ice-cover breakup based on stream water temperature along the Athabasca River.

MESH-RBM also provides ecological insights. Many fish species depend on cyclical patterns of river flows and water temperature to complete their life cycle. Changes in streamflow or water temperature can affect survival rates. For example, Morales-Marín, Rokaya, et al. (2019) studied the effects of changes in future streamflow and water temperature on habitat suitability for the Athabasca Rainbow Trout (considered as a ‘species at risk’) in the Athabasca River. Related developments include the capability to simulate other water quality variables. MESH-SED, based on SHESED (Wicks & Bathurst, 1996), is currently under development to simulate sediment transport and nutrient loads.

MESH has also been routinely coupled with the RIVICE hydrodynamic river ice model developed by ECCC (Environment

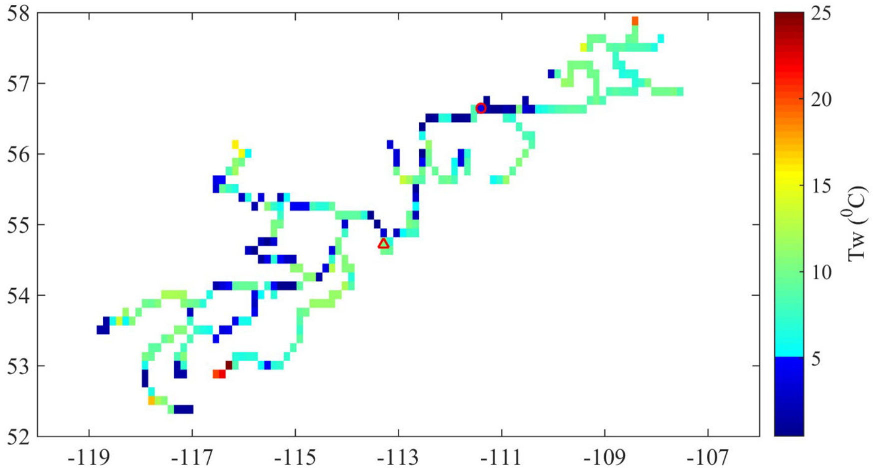

FIGURE 10 Forecast from 20 April 2018 for 28 April 2018 breakup for the Athabasca River in western Canada. The x-axis is longitude and y-axis is latitude. The spatial resolution of the grid is 0.125°. The coloured grids represent the river network. The red circle denotes the location of the town of Fort McMurray and the red triangle indicates the location of the town of Athabasca.
Figure adopted from Rokaya et al., (2020a) with permission

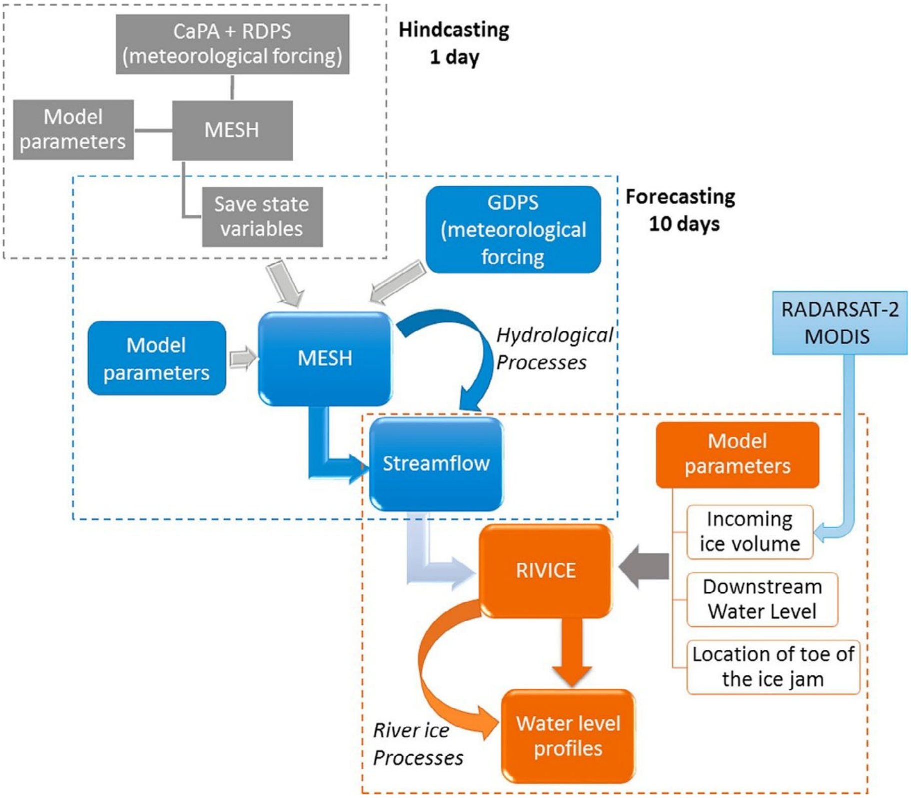

FIGURE 11 Schematic diagram of the coupled ice-jam flood forecasting system. Figure adopted from Lindenschmidt et al. (2019) with permission

Canada, 2013) for assessment of more complex river ice processes, such as ice-jam flooding. MESH-RIVICE has enabled examination of the role of river discharge in ice cover formation and breakup processes (Rokaya, Wheater, & Lindenschmidt, 2018b), evaluation of the relative impacts of climate and regulation on ice-jam flooding (Rokaya, Peters, et al., 2019b; for the Peace River basin), assessment of ice-jam flood risk under future climate (Das et al., 2020; Rokaya, Morales-Marín, et al., 2019a) and the development of one of the world's first process-based operational ice-jam flood forecasting systems (Lindenschmidt et al., 2019), see Figure 11, now implemented for the Churchill River, Labrador, Canada.

6 | MODEL APPLICATIONS

The Mackenzie River Basin (MRB; Figure 1) is the largest river basin in Canada (1.8 million km^2), discharges more than 300 km^3/year of water to the Arctic Ocean and influences regional climate as well as global atmospheric circulation (Woo, 2008). Exceptionally high rates of warming have been observed in the northern MRB (DeBeer et al., 2016) and climate change models predict that these trends will continue, with enhanced precipitation and shifts to more rainfall than snowfall (DeBeer et al., 2021; Stewart et al., 2019). Hydrological modelling of the MRB embodies the challenges of cold regions

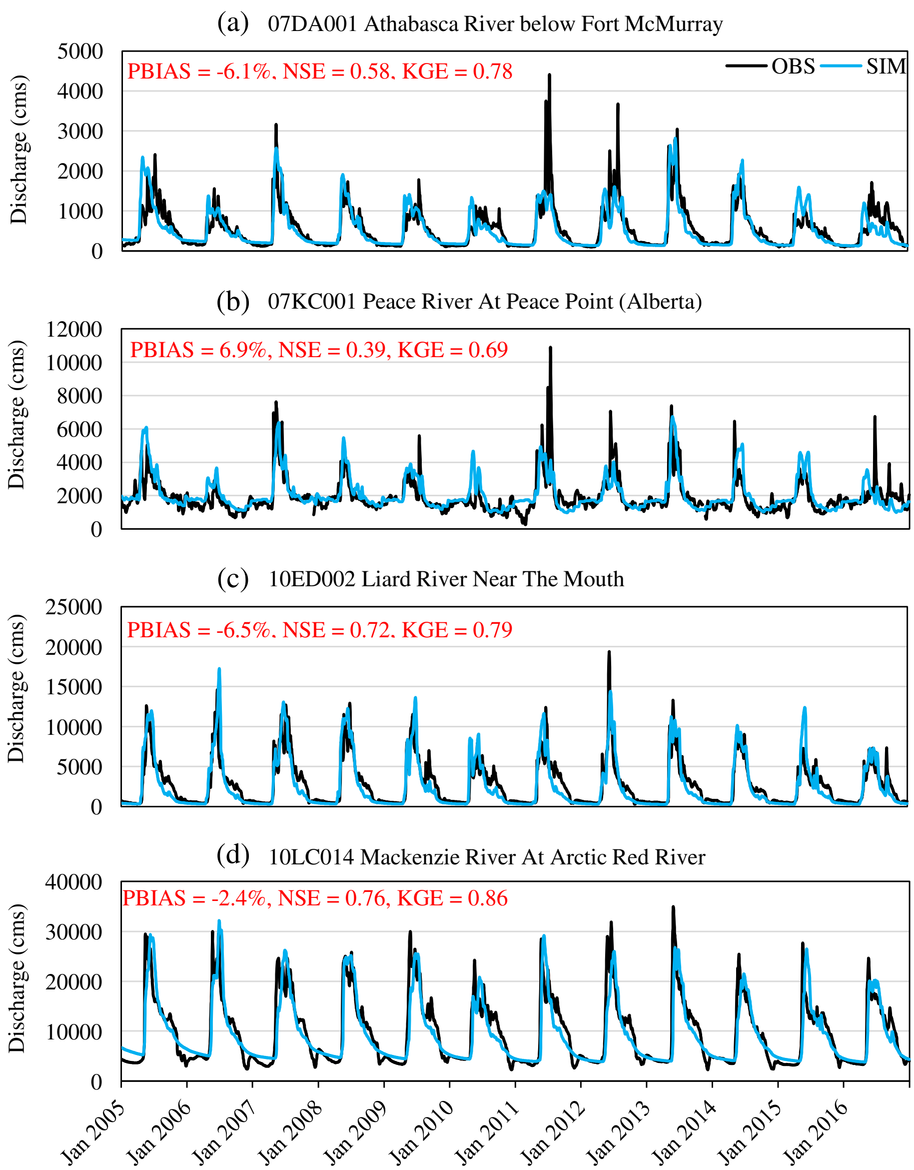

FIGURE 12 Hydrographs of major tributaries and outlet of the Mackenzie River showing goodness of fit and bias estimates over the simulation period (2005–2016). This includes both calibration and validation periods. Gauge locations are shown in Figure 1

modelling discussed above, including the fact that it is relatively data sparse and observational data are subject to large uncertainty.

The western tributaries of the Mackenzie originate from the Canadian Rockies and the Mackenzie Mountains and are relatively steep, while the Eastern tributaries lie in the Canadian Shield with several interconnected and large lakes and wetlands including Great Slave Lake, Great Bear Lake and Lake Athabasca – three of the largest lakes in the world (Figure 1). Over half the MRB is underlain by permafrost that is warming, resulting in permafrost thaw and vegetation change. To investigate the impacts of climate and land cover changes on MRB hydrology, MESH was configured as discussed in Section 4.1.3 above with a deep soil profile (∼50 m) and organic surface soils to enable simulation of permafrost evolution and a spin-up strategy to initialize the soil profile states, validated using experimental data. The model improvements to represent basin regulation (see Section 4.3 above) were used to simulate the Bennett Dam in the Peace River headwaters. Enhancements to the glacier module (Section 4.1.4) were used for glaciated parts in the western mountains. Blowing snow (Section 4.1.1) was activated for simulation of snow accumulation, transport, sublimation, redistribution and melt, affecting water balance and streamflow at the basin scale. Careful parameterization of major lakes, and calibration of sensitive parameters (as defined by SA studies—Section 4.4) resulted in a high-fidelity model as indicated by streamflow simulated at major flow gauge stations (Figure 12). The fidelity of the model has been assessed for permafrost (Figure 3) and hydrological fluxes and states including evapotranspiration and snowpack. Bahrami et al. (2021) show an evaluation for the Liard sub-basin of simulated total water storage in comparison to GRACE data and SWE against Canadian Meteorological Centre (CMC) snowpack data.

Modelling the MRB has proven to be demanding, not least because the large computational requirements and the complexities around permafrost simulation, and only preliminary simulations of future change are currently available for the basin. However, Rokaya et al. (2020a, 2020b) assessed the impacts of climate change on the

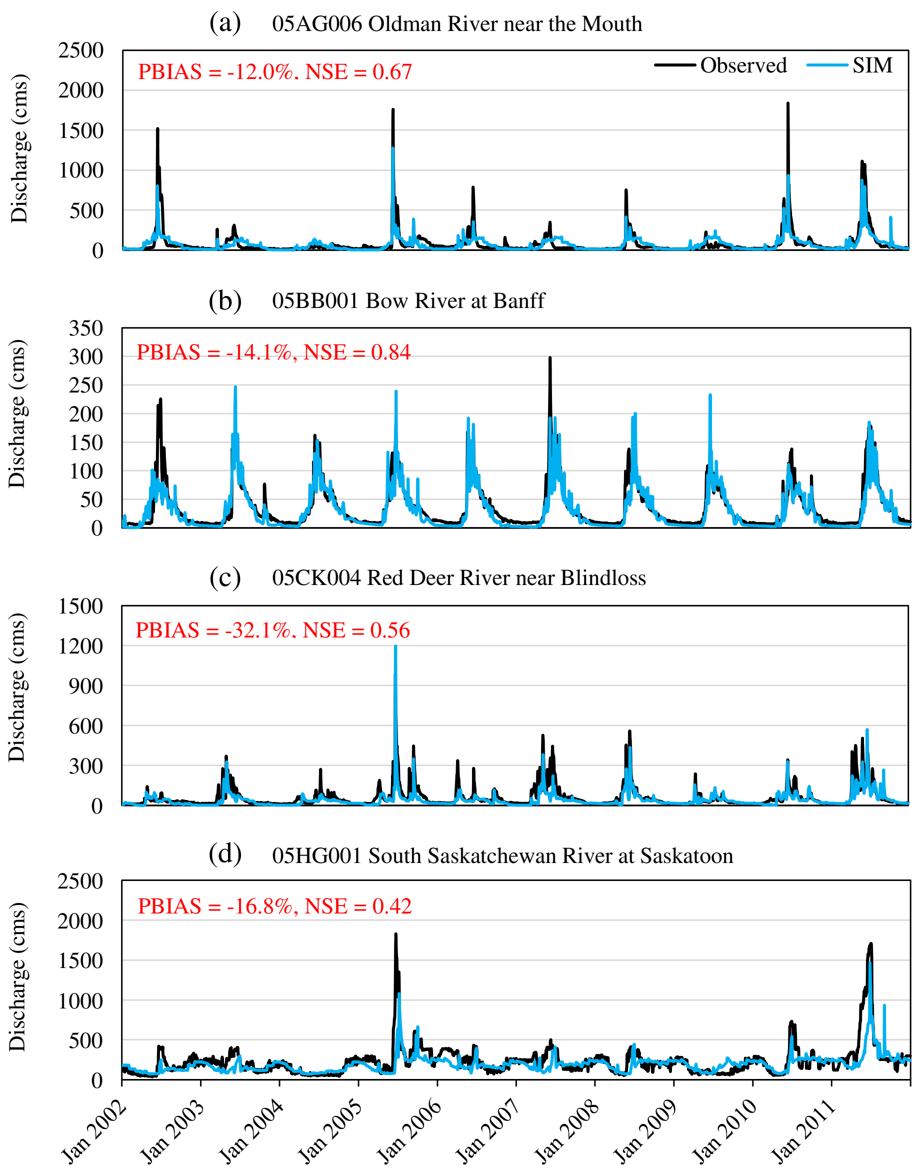

FIGURE 13 MESH model long term average streamflow output for major sub-basins of the Saskatchewan River Basin. This period includes calibration and validation periods. Gauge locations are shown in Figure 1

Smoky River, a major sub-basin of the Peace tributary of the MRB, using a bias-corrected 15-member ensemble from the Canadian Regional Climate Model version 4 (CanRCM4) (Asong et al., 2020). The results indicate significant changes to the flow regime with increased winter and spring flows and lower summer flows for the end of the 21st century compared to the baseline period (1981–2010), with earlier peaks for open water flooding (see fig. 6 in Rokaya et al., 2020a). The projected changes are likely to have significant impacts on the ecologically sensitive Peace Athabasca Delta downstream. A similar methodology is proposed to assess the climate change impacts over the entire MRB.

Another large-scale MESH application is the 406 000 km^2 Saskatchewan River Basin (SaskRB) (Figure 1). This system is characterized by hydrologically distinct cold regions, including the Rocky Mountains, Boreal Forest and semi-arid Canadian Prairies, and supplies water to major cities and irrigated farmland in the region. The different hydrological and land surface processes are further complicated by extensive water management, including multi-use reservoirs, diversions, irrigation and inter-jurisdictional water sharing policy (Wheater & Gober, 2013). Irrigation (approximately 1.5 million acres irrigated almost exclusively from surface water) accounts for the largest consumptive use in the basin. Eighteen major reservoirs impact the natural flow regime and are explicitly included in this model. Glaciers account for a small fraction of the basin (340 km^2) but strongly impact summer headwater flows.

Dominant process parameters were derived from satellite vegetation cover estimates, soil, glacier and drainage surveys, irrigation inventories, and digital elevation models. Parameters that could not be estimated based on available data or physical characteristics were optimized using multi-objective calibration; reservoirs and irrigation were simulated as described above. Figure 13 shows the model streamflow output at the major sub-basin outlets. The model provides a suitable basis for water balance evaluation and examination of the future impacts of climate change and increasing water use.

7 | DISCUSSION AND CONCLUSIONS

Modelling cold region hydrology at the large river basin scale remains an area of major importance globally, but, as this paper has illustrated, is associated with considerable challenges.

One of the important conclusions from this work is that the sensitivity of cold region processes to temperature change poses a major challenge for model forcing data, particularly when derived from global climate models for future scenarios. Biases of a few degrees in temperature are common, yet have profound consequences for modelling fidelity, for instance in calculating the correct precipitation phase, blowing snow transport, intercepted snow unloading, snowmelt, icemelt and thaw of frozen ground. Not only should biases in temperature be small, but the temporal sequences of temperature, precipitation, humidity, solar radiation and wind speed need to be realistic over sub-daily and seasonal time periods in order to correctly calculate cold regions processes due to the coupling of mass and energy balance equations.

The paper has also demonstrated that without careful attention to key features of cold region hydrology, land surface schemes can produce misleading results. Blowing snow and permafrost were just two examples presented above. The implications for future developments are discussed below.

As highlighted above, several important cold region processes depend on topography. Accurate representation of coupled energy and related mass fluxes is a key aspect of cold region modelling, and the importance of elevation, slope and aspect in determining energy budgets in mountain regions focusses attention on the need for refined model spatial resolution to resolve topography. Similarly, blowing snow transport and sublimation processes, which are relevant for alpine, arctic and prairie environments, depend on wind flow over complex terrain. Accurate calculation of this windflow requires high resolution representations of topography and boundary layer or computational fluid dynamics wind flow models. Sublimation losses from blowing snow scale up to the basin scale in mass balances and snow redistribution due to transport controls the snow cover depletion curve, meltwater supplies for prairie ponds and mountain glaciers and the resulting meltwater hydrographs. Thus, the long-term trend of increased model spatial resolution can be expected to deliver improved model process fidelity, and while there are benefits to the atmospheric modelling community in maintaining regular grids, adaptive grids can produce improved performance while significantly reducing computational burden (Marsh et al., 2020, b; Vionnet et al., 2021). Advances these methods are providing for continental scale calculations of complex terrain wind flow, snow redistribution, snowmelt on slopes and even shading of solar radiation by high mountains and are considered essential to advance mountain cold regions models. The blowing snow algorithms discussed above have been shown to deliver important benefits for improved process representation but depend on sub-grid approximations and so have inherent assumptions and simplifications. Increased integration between high-resolution hydrological and meteorological models and the availability of integrated land surface schemes at higher resolutions would enable fully-coupled modelling of wind and blowing snow.

Turning to the subsurface, thawing permafrost has major implications for society, ranging from threats to the built environment, terrestrial ecosystem disturbance, changes in water storage and the release of methane. However modelling permafrost change remains a significant challenge for all modelling groups in the global community. There is a major challenge in initializing a non-stationary permafrost field, requiring long spin-up times and deep profiles. MESH applications to western Canada have been successful in simulating the continuous permafrost of higher latitudes, and correctly indicating the lack of permafrost in the south. Discontinuous permafrost is more challenging, and while the advances in MESH discussed above are state-of-the-art, improving representation of transient permafrost conditions is an ongoing pursuit.

More generally, there is scope for improved physically based modelling of frozen soils. Basic relationships such as the soil freezing characteristic curve, based on capillary effects, have been questioned due to the potential importance of capillary-solute effects (Amankwah et al., 2021). And while parametric relationships based on simplifications of more computationally intensive physics based models, such as those for infiltration into frozen soils (e.g. Zhao & Gray, 1999), have been at the heart of many cold region hydrological models, and have a major benefit in constraining models, ideally, there would be progress towards implementing a full solution of the Richards' equation for frozen and partially frozen soils. All soil water movement simulations are sensitive to soil physical properties, and much remains to be done to evaluate effective parameters—current modelling generally uses soil textural classes to infer parameterizations. These do not always reflect realistic soil textures and hydrophysical properties and as MESH applications in the Boreal Forest have shown, this can lead to suboptimal simulations.

Representations of the role of surface water storage in small ponds and lakes in the glacial-till underlain Canadian Prairies, bedrock Canadian Shield and permafrost underlain Arctic tundra plains in hydrological models has been a great challenge to successful hydrological modelling of these environments. Problems of variable contributing area and connected areas and episodic changes in these areas during high runoff events have confounded modellers of these environments for generations. MESH has advanced these representations, but more needs to be done to parameterize the dynamical connected and contributing fractions of Prairie basins using parameterizations such as those proposed by Shook et al. (2021) and to test and further develop these parameterisations for the Canadian Shield and arctic tundra basins.

As discussed above, glaciers are an important feature of mountain cold region landscapes and hydrology but have been rapidly decreasing in volume and areal extent in many regions, due to global warming. Glacier melt rates in the Canadian Rockies have increased not only from warming temperatures, but due to decreasing snowcover on glaciers, increased rainfall and reduced ice albedo from soot deposits from upwind wildfires and algae growth (Aubry-Wake et al., n.d.; Pradhananga & Pomeroy, 2022). Implications for downstream water users remain unclear, given the challenges of modelling these changes and uncertainty in quantifying the contribution of icemelt from glaciers. Here, improved simulation of glacier energetics and melt rates are reported, but most large-scale physically based models, including MESH, have not yet included full glacier ice movement dynamics, due in part to limited data on glacier volumes—this remains another outstanding challenge. The glacier routines in MESH do not resolve the processes of firnification, debris-covered icemelt, sub-glacier water flow and the critically important shifts in surface albedo as snow, firn and ice are exposed during the course of a melt season. Sub-glacial hydraulics controls routing and current routing does not fully represent the influences of supra and sub-glacial channels, storage and conditions at the glacier bed interface nor sub-glacier flow through bedrock and moraine on hydraulics (DeBeer et al., 2020; Pradhananga & Pomeroy, 2022). There are feedbacks amongst these changes and their drivers, further complicating the responses to climate and mass balance.

Notably, remote sensing data has shown important benefits, particularly for large scale application and where surface observations are sparse. In particular, the ability to constrain water storage using GRACE has improved simulation performance and reduced parameter uncertainty (Yassin et al., 2017). The potential of water level assimilation, through missions such as SWOT, is currently being explored and offers major promise in understanding reservoir management as well as constraining model flow simulations. There is major scope for the future use of remote sensing data to inform the representation of landscape heterogeneity and constrain simulation of land-atmosphere fluxes; this is of course an area that would benefit hydrological modelling in general.

It was also shown that current tools for sensitivity analysis provide useful insights into high dimensional models such as MESH, and that multi-objective performance assessment can facilitate the use of multiple data sources in model conditioning.

As discussed above, Canada's MESH model has undergone significant advances in recent years, in process representation and modelling flexibility. Parameters that were hard coded are now accessible to adapt algorithms to regional hydrology. The model includes lateral fluxes, though could be further improved for groundwater and wetland processes. Modelling landscape change remains a challenge. Current work is addressing the need for dynamic modelling of glacier geometry. A related challenge applies to the changing topography, connectivity and vegetation associated with permafrost thaw. These issues are not dealt with satisfactorily by any large scale model and represent the forefront for model advancement—further, this is critical to full system representation under future climate and Earth system change.

The capability of models such as MESH for large scale and cold region flow forecasting is demonstrated by the implementation of MESH for operational flood forecasting for the 0.3 million km^2 Yukon River basin (Elshamy et al., 2020, n. d.) and a reach of the Athabasca River (Lindenschmidt et al., 2019). Going forward, ECCC, provincial and territorial partners, and their partners in academia such as GWF are working together to develop national-scale capability and consistency in support of operational forecasting and decision making. The advancements made to improve the science base of MESH and its technical capabilities directly feed into this effort, representing an important technology transfer.

In summary, the physically-based MESH model is an example of the current generation of cold region models that is applicable to large river basins world-wide, such as those emanating from the Andes, High Mountain Asia, the Alps and Pyrenees, the North American Cordillera and circumpolar high latitudes, where snow and ice play a role in the hydrological cycle and parameter identification is often challenged by ungauged basins and sparse geospatial information. Its close association with a legacy of several decades of Canadian observational and modelling experience and process hydrology research has been important in developing improved scientific as well as technical capabilities. It is now a powerful tool for a wide range of applications, including simulation of climate and other anthropogenic change, from point to regional and global scales. It also provides an invaluable platform to analyse and assimilate improvements in hydrological, hydro-ecological and hydro-meteorological process understanding. Nevertheless, this community model remains a work in progress, and we look forward to exploring the potential of new science, data and modelling tools as we continue to enhance the platform's capability.

ACKNOWLEDGEMENTS

Funding for this research from the Natural Sciences and Engineering Research Council of Canada's Changing Cold Regions Network and Discovery Grants, the Canada First Research Excellence Fund's Global Water Futures programme, the Canada Excellence Research Chair in Water Security and Canada Research Chair in Water Resources and Climate Change at the University of Saskatchewan and Environment and Climate Change Canada is gratefully acknowledged. The authors particularly wish to recognize the seminal contribution of the late Prof. Eric (Ric) Soulis, University of Waterloo, to the initial development of MESH.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request. Data are also accessible through the CCRN website (http://www.ccrnetwork.ca) and the Global Water Futures program website.

ORCID

John W. Pomeroy https://orcid.org/0000-0002-4782-7457
Bruce Davison https://orcid.org/0000-0003-2160-560X
Mohamed Elshamy https://orcid.org/0000-0002-3621-0021
Fuad Yassin https://orcid.org/0000-0001-8179-7928
Prabin Rokaya https://orcid.org/0000-0003-1999-495X
Daniel Princz https://orcid.org/0000-0001-9605-1184
Chris M. DeBeer https://orcid.org/0000-0003-1828-0293
Andrew M. Ireson https://orcid.org/0000-0003-1957-7355
Saman Razavi https://orcid.org/0000-0003-1870-5810
Karl-Erich Lindenschmidt https://orcid.org/0000-0001-6348-2295
Amin Elshorbagy https://orcid.org/0000-0002-5740-8029

Mohamed Abdelhamed https://orcid.org/0000-0001-7229-6670
Amin Haghnegahdar https://orcid.org/0000-0002-1917-6001
Ala Bahrami https://orcid.org/0000-0002-2650-1183

REFERENCES

Abdelhamed, M. S., Elshamy, M. E., Wheater, H. S., & Razavi, S. (2022). Hydrologic-land surface modelling of the Canadian sporadic-discontinuous permafrost: Initialization and uncertainty propagation. *Hydrological Processes*, *36*(3), e14509. https://doi.org/10.1002/hyp.14509

Ahmed, M. I., Elshorbagy, A., & Pietroniro, A. (2020). A novel model for storage dynamics simulation and inundation mapping in the prairies. *Environmental Modelling & Software*, *133*, 104850. https://doi.org/10.1016/j.envsoft.2020.104850

Ahmed, M. I., Elshorbagy, A., Pietroniro, A., & Princz, D. (2021). Improving the representation of the non-contributing area dynamics in land surface models for better simulation of prairie hydrology. *Journal of Hydrology*, *600*, 126562. https://doi.org/10.1016/j.jhydrol.2021.126562

Alexeev, V. A., Nicolsky, D. J., Romanovsky, V. E., & Lawrence, D. M. (2007). An evaluation of deep soil configurations in the CLM3 for improved representation of permafrost. *Geophysical Research Letters*, *34*(9), 5. https://doi.org/10.1029/2007GL029536

Amankwah, S. K., Ireson, A. M., Maulé, C., Brannen, R., & Mathias, S. A. (2021). A Model for the Soil Freezing Characteristic Curve That Represents the Dominant Role of Salt Exclusion. *Water Resources Research*, *57*(8), e2021WR030070. https://doi.org/10.1029/2021WR030070

Asong, Z. E., Elshamy, M. E., Princz, D., Wheater, H. S., Pomeroy, J. W., Pietroniro, A., & Cannon, A. (2020). High-resolution meteorological forcing data for hydrological modelling and climate change impact analysis in the Mackenzie River basin. *Earth System Science Data*, *12*(1), 629–645. https://doi.org/10.5194/essd-12-629-2020

Aubry-Wake, C., Bertoncini, A., & Pomeroy, J. W. (n.d.). Fire and ice: The impact of wildfire-affected albedo and irradiance on glacier melt. *Earth's Future*. submitted.

Bahrami, A., Goïta, K., Magagi, R., Davison, B., Razavi, S., Elshamy, M., & Princz, D. (2021). Data assimilation of satellite-based terrestrial water storage changes into a hydrology land-surface model. *Journal of Hydrology*, *597*, 125744. https://doi.org/10.1016/j.jhydrol.2020.125744

Barr, A. G., Van der Kamp, G., Black, T. A., McCaughey, J. H., & Nesic, Z. (2012). Energy balance closure at the BERMS flux towers in relation to the water balance of the White Gull Creek watershed 1999–2009. *Agricultural and Forest Meteorology*, *153*, 3–13. https://doi.org/10.1016/j.agrformet.2011.05.017

Bartlett, P. A., Harry McCaughey, J., Lafleur, P. M., & Verseghy, D. L. (2003). Modelling evapotranspiration at three boreal forest stands using the CLASS: Tests of parameterizations for canopy conductance and soil evaporation. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *23*(4), 427–451. https://doi.org/10.1002/joc.884

Bartlett, P. A., MacKay, M. D., & Verseghy, D. L. (2006). Modified snow algorithms in the Canadian land surface scheme: Model runs and sensitivity analysis at three boreal forest stands. *Atmosphere-Ocean*, *44*(3), 207–222. https://doi.org/10.3137/ao.440301

Bartlett, P. A., & Verseghy, D. L. (2015). Modified treatment of intercepted snow improves the simulated forest albedo in the Canadian land surface scheme. *Hydrological Processes*, *29*(14), 3208–3226. https://doi.org/10.1002/hyp.10431

Bélair, S., Brown, R., Mailhot, J., Bilodeau, B., & Crevier, L. P. (2003). Operational implementation of the ISBA land surface scheme in the Canadian regional weather forecast model. Part II: Cold season results. *Journal of Hydrometeorology*, *4*(2), 371–386. https://doi.org/10.1175/1525-7541(2003)4%3C371:OIOTIL%3E2.0.CO;2

Bélair, S., Crevier, L. P., Mailhot, J., Bilodeau, B., & Delage, Y. (2003). Operational implementation of the ISBA land surface scheme in the Canadian regional weather forecast model. Part I: Warm season results. *Journal of Hydrometeorology*, *4*(2), 352–370. https://doi.org/10.1175/1525-7541(2003)4%3C352:OIOTIL%3E2.0.CO;2

Beltaos, S., & Prowse, T. (2009). River-ice hydrology in a shrinking cryosphere. *Hydrological Processes: An International Journal*, *23*(1), 122–144. https://doi.org/10.1002/hyp.7165

Benoit, R., Pellerin, P., Kouwen, N., Ritchie, H., Donaldson, N., Joe, P., & Soulis, E. D. (2000). Toward the use of coupled atmospheric and hydrologic models at regional scale. *Monthly Weather Review*, *128*(6), 1681–1706. https://doi.org/10.1175/1520-0493(2000)128%3C1681:TTUOCA%3E2.0.CO;2

Blyth, E. (2001). Relative influence of vertical and horizontal processes in large-scale water and energy balance modelling. In A. J. Dolman, A. J. Hall, M. L. Kavvas, T. Oki, & J. W. Pomeroy (Eds.), *Soil – vegetation atmosphere transfer schemes and large-scale hydrological models* (Vol. 270, pp. 3–10). IAHS Publication.

Brandt, J. P., Flannigan, M. D., Maynard, D. G., Thompson, I. D., & Volney, W. J. A. (2013). An introduction to Canada's boreal zone: Ecosystem processes, health, sustainability, and environmental issues. *Environmental Reviews*, *21*(4), 207–226. https://doi.org/10.1139/er-2013-0040

Brown, R., Bartlett, P., MacKay, M., & Verseghy, D. (2006). Evaluation of snow cover in CLASS for SnowMIP. *Atmosphere-Ocean*, *44*(3), 223–238. https://doi.org/10.3137/ao.440302

Brutsaert, W. (1975). On a derivable formula for long-wave radiation from clear skies. *Water Resources Research*, *11*(5), 742–744. https://doi.org/10.1029/WR011i005p00742

Buck, A. L. (1981). New equations for computing vapor pressure and enhancement factor. *Journal of Applied Meteorology and Climatology*, *20*(12), 1527–1532. https://doi.org/10.1175/1520-0450(1981)020<1527:NEFCVP>2.0.CO;2

Burke, E. J., Zhang, Y., & Krinner, G. (2020). Evaluating permafrost physics in the coupled model Intercomparison project 6 (CMIP6) models and their sensitivity to climate change. *The Cryosphere*, *14*(9), 3155–3174. https://doi.org/10.5194/tc-14-3155-2020

Chadburn, S., Burke, E., Essery, R., Boike, J., Langer, M., Heikenfeld, M., Cox, P., & Friedlingstein, P. (2015). An improved representation of physical permafrost dynamics in the JULES land-surface model. *Geoscientific Model Development*, *8*(5), 1493–1508. https://doi.org/10.5194/gmd-8-1493-2015

Clapp, R. B., & Hornberger, G. M. (1978). Empirical equations for some soil hydraulic properties. *Water Resources Research*, *14*(4), 601–604. https://doi.org/10.1029/WR014i004p00601

Clark, M. P., Nijssen, B., Lundquist, J. D., Kavetski, D., Rupp, D. E., Woods, R. A., Freer, J. E., Gutmann, E. D., Wood, A. W., Brekke, L. D., Arnold, J. R., Gochis, D. J., & Rasmussen, R. M. (2015). A unified approach for process-based hydrologic modeling: 1. *Modeling concept. Water Resources Research*, *51*(4), 2498–2514. https://doi.org/10.1002/2015WR017198

Clark, M. P., Zolfaghari, R., Green, K. R., Trim, S., Knoben, W. J. M., Bennett, A., Nijssen, B., Ireson, A., & Spiteri, R. J. (2021). The numerical implementation of land models: Problem formulation and laugh tests. *Journal of Hydrometeorology*, *22*(6), 1627–1648. https://doi.org/10.1175/JHM-D-20-0175.1

Cosby, B. J., Hornberger, G. M., Clapp, R. B., & Ginn, T. (1984). A statistical exploration of the relationships of soil moisture characteristics to the physical properties of soils. *Water Resources Research*, *20*(6), 682–690. https://doi.org/10.1029/WR020i006p00682

Côté, J., & Konrad, J. M. (2005). A generalized thermal conductivity model for soils and construction materials. *Canadian Geotechnical Journal*, *42*(2), 443–458. https://doi.org/10.1139/t04-106

Das, A., Reed, M., & Lindenschmidt, K. E. (2018). Sustainable ice-jam flood management for socio-economic and socio-ecological systems. *Water*, *10*(2), 135. https://doi.org/10.3390/w10020135

Das, A., Rokaya, P., & Lindenschmidt, K. E. (2020). Ice-jam flood risk assessment and hazard mapping under future climate. *Journal of Water Resources Planning and Management*, *146*(6), 04020029. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001178

Davison, B., Pietroniro, A., Fortin, V., Leconte, R., Mamo, M., & Yau, M. K. (2016). What is missing from the prescription of hydrology for land surface schemes? *Journal of Hydrometeorology*, *17*(7), 2013–2039. https://doi.org/10.1175/JHM-D-15-0172.1

Davison, B., Pohl, S., Domes, P., Marsh, P., Pietroniro, A., & MacKay, M. (2006). Characterizing snowmelt variability in a land-surface-hydrologic model. *Atmosphere-Ocean*, *44*(3), 271–287. https://doi.org/10.3137/ao.440305

de Vrese, P., Schulz, J. P., & Hagemann, S. (2016). On the representation of heterogeneity in land-surface–atmosphere coupling. *Boundary-Layer Meteorology*, *160*(1), 157–183.

DeBeer, C. M., Sharp, M., & Schuster-Wallace, C. (2020). Glaciers and ice sheets. In M. I. Goldstein & D. A. DellaSala (Eds.), *Encyclopedia of the World's biomes*, *4* (pp. 182–194). Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.12441-8

DeBeer, C. M., Wheater, H. S., Carey, S. K., & Chun, K. P. (2016). Recent climatic, cryospheric, and hydrological changes over the interior of western Canada: A review and synthesis. *Hydrology and Earth System Sciences*, *20*(4), 1573–1598. https://doi.org/10.5194/hess-20-1573-2016

DeBeer, C. M., Wheater, H. S., Pomeroy, J. W., Barr, A. G., Baltzer, J. L., Johnstone, J. F., Turetsky, M. R., Stewart, R. E., Hayashi, M., van der Kamp, G., Marshall, S., Campbell, E., Marsh, P., Carey, S. K., Quinton, W. L., Li, Y., Razavi, S., Berg, A., McDonnell, J. J., Spence, C., … Pietroniro, A. (2021). Summary and synthesis of changing cold regions network (CCRN) research in the interior of western Canada–part 2: Future change in cryosphere, vegetation, and hydrology. *Hydrology and Earth System Sciences*, *25*(4), 1849–1882. https://doi.org/10.5194/hess-25-1849-2021

Dobinski, W. (2011). Permafrost. *Earth-Science Reviews*, *108*(3-4), 158–169. https://doi.org/10.1016/j.earscirev.2011.06.007

Dornes, P. F., Pomeroy, J. W., Pietroniro, A., & Verseghy, D. L. (2008). Effects of spatial aggregation of initial conditions and forcing data on modeling snowmelt using a land surface scheme. *Journal of Hydrometeorology*, *9*(4), 789–803. https://doi.org/10.1175/2007JHM958.1

Dornes, P. F., Tolson, B. A., Davison, B., Pietroniro, A., Pomeroy, J. W., & Marsh, P. (2008). Regionalisation of land surface hydrological model parameters in subarctic and arctic environments. *Physics and Chemistry of the Earth, Parts A/B/C*, *33*(17-18), 1081–1089. https://doi.org/10.1016/j.pce.2008.07.007

Dümenil, L., & Todini, E. (1992). A rainfall–runoff scheme for use in the Hamburg climate model. In *Advances in theoretical hydrology* (pp. 129–157). Elsevier. https://doi.org/10.1016/B978-0-444-89831-9.50016-8

Elshamy, M. E., Loukili, Y., Pomeroy, J. W., Pietroniro, A., Richard, D., & Princz, P. (n. d.). Physically based cold regions river flood prediction in data-sparse regions: The Yukon River Basin flow forecasting system. *Journal of Flood Risk Management*.

Elshamy, M. E., Loukili, Y., Princz, D., Richard, D., Tesemma, Z., & Pomeroy, J. W. (2020). Yukon River Basin Streamflow Forecasting System, Centre for Hydrology Report #16, Saskatoon, Canada, 59pp. https://research-groups.usask.ca/hydrology/documents/reports/chrpt16_yukon-river-basin-streamflow-forecasting-system_-finalreport_2020.pdf

Elshamy, M. E., Princz, D., Sapriza-Azuri, G., Abdelhamed, M. S., Pietroniro, A., Wheater, H. S., & Razavi, S. (2020). On the configuration and initialization of a large-scale hydrological land surface model to represent permafrost. *Hydrology and Earth System Sciences*, *24*(1), 349–379. https://doi.org/10.5194/hess-24-349-2020

Environment Canada. (2013). RIVICE Model - User's Manual. http://giws.usask.ca/rivice/Manual/RIVICE_Manual_2013-01-11.pdf

Essery, R., Li, L., & Pomeroy, J. (1999). A distributed model of blowing snow over complex terrain. *Hydrological Processes*, *13*(14-15), 2423–2438.

Evensen, G., & Van Leeuwen, P. J. (2000). An ensemble Kalman smoother for nonlinear dynamics. *Monthly Weather Review*, *128*(6), 1852–1867. https://doi.org/10.1175/1520-0493(2000)128<1852:AEKSFN>2.0.CO;2

Fang, X., & Pomeroy, J. W. (2009). Modelling blowing snow redistribution to prairie wetlands. *Hydrological Processes: An International Journal*, *23*(18), 2557–2569.

Fang, X., Pomeroy, J. W., DeBeer, C. M., Harder, P., & Siemens, E. (2019). Hydrometeorological data from Marmot Creek Research Basin. *Canadian Rockies. Earth System Science Data*, *11*(2), 455–471. https://doi.org/10.5194/essd-11-455-2019

Fang, X., Pomeroy, J. W., Ellis, C. R., MacDonald, M. K., DeBeer, C. M., & Brown, T. (2013). Multi-variable evaluation of hydrological model predictions for a headwater basin in the Canadian Rocky Mountains. *Hydrology and Earth System Sciences*, *17*(4), 1635–1659. https://doi.org/10.5194/hess-17-1635-2013

Fang, X., Pomeroy, J. W., Westbrook, C. J., Guo, X., Minke, A. G., & Brown, T. (2010). Prediction of snowmelt derived streamflow in a wetland dominated prairie basin. *Hydrology and Earth System Sciences*, *14*(6), 991–1006. https://doi.org/10.5194/hess-14-991-2010

Fayad A., & Pomeroy, J. W. (n.d.). Evaluation of snowpack using a physically parameterized hydrological land surface scheme and in-situ meteorological forcing in the Canadian Rockies. in preparation.

Gaborit, É., Fortin, V., Xu, X., Seglenieks, F., Tolson, B., Fry, L. M., Hunter, T., Anctil, F., & Gronewold, A. D. (2017). A hydrological prediction system based on the SVS land-surface scheme: Efficient calibration of GEM-hydro for streamflow simulation over the Lake Ontario basin. *Hydrology and Earth System Sciences*, *21*(9), 4825–4839. https://doi.org/10.5194/hess-21-4825-2017

Ganji, A., Sushama, L., Verseghy, D., & Harvey, R. (2017). On improving cold region hydrological processes in the Canadian land surface scheme. *Theoretical and Applied Climatology*, *127*(1-2), 45–59. https://doi.org/10.1007/s00704-015-1618-4

Garnier, B. J., & Ohmura, A. (1968). A method of calculating the direct shortwave radiation income of slopes. *Journal of Applied Meteorology and Climatology*, *7*(5), 796–800. https://doi.org/10.1175/1520-0450(1968)007<0796:AMOCTD>2.0.CO;2

Garnier, B. J., & Ohmura, A. (1970). The evaluation of surface variations in solar radiation income. *Solar Energy*, *13*(1), 21–34. https://doi.org/10.1016/0038-092X(70)90004-6

Giorgi, F., Francisco, R., & Pal, J. (2003). Effects of a subgrid-scale topography and land use scheme on the simulation of surface climate and hydrology. Part I: Effects of temperature and water vapor disaggregation. *Journal of Hydrometeorology*, *4*(2), 317–333. https://doi.org/10.1175/1525-7541(2003)4<317:EOASTA>2.0.CO;2

Haghnegahdar, A., & Razavi, S. (2017). Insights into sensitivity analysis of earth and environmental systems models: On the impact of parameter perturbation scale. *Environmental Modelling & Software*, *95*, 115–131. https://doi.org/10.1016/j.envsoft.2017.03.031

Haghnegahdar, A., Razavi, S., Yassin, F., & Wheater, H. (2017). Multicriteria sensitivity analysis as a diagnostic tool for understanding model behaviour and characterizing model uncertainty. *Hydrological Processes*, *31*(25), 4462–4476. https://doi.org/10.1002/hyp.11358

Hamman, J. J., Nijssen, B., Bohn, T. J., Gergel, D. R., & Mao, Y. (2018). The variable infiltration capacity model version 5 (VIC-5): Infrastructure improvements for new applications and reproducibility. *Geoscientific Model Development*, *11*(8), 3481–3496. https://doi.org/10.5194/gmd-11-3481-2018

Hanasaki, N., Kanae, S., & Oki, T. (2006). A reservoir operation scheme for global river routing models. *Journal of Hydrology*, *327*(1-2), 22–41. https://doi.org/10.1016/j.jhydrol.2005.11.011

Harder, P., & Pomeroy, J. (2013). Estimating precipitation phase using a psychrometric energy balance method. *Hydrological Processes*, *27*(13), 1901–1914. https://doi.org/10.1002/hyp.9799

Hedstrom, N. R., & Pomeroy, J. W. (1998). Measurements and modelling of snow interception in the boreal forest. *Hydrological Processes*, *12*(10-11), 1611–1625. https://doi.org/10.1002/(SICI)1099-1085(199808/09)12:10/11%3C1611::AID-HYP684%3E3.0.CO;2-4

Hjort, J., Karjalainen, O., Aalto, J., Westermann, S., Romanovsky, V. E., Nelson, F. E., Etzelmüller, B., & Luoto, M. (2018). Degrading permafrost puts Arctic infrastructure at risk by mid-century. *Nature Communications*, *9*, 5147. https://doi.org/10.1038/s41467-018-07557-4

Hossain, K. (2017). *Towards a systems modelling approach for a large-scale Canadian prairie watershed* [M.Sc. Thesis, Department of Civil and Geological Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada]. http://hdl.handle.net/10388/8345.

Husain, S. Z., Alavi, N., Bélair, S., Carrera, M., Zhang, S., Fortin, V., Abrahamowicz, M., & Gauthier, N. (2016). The multibudget soil, vegetation, and snow (SVS) scheme for land surface parameterization: Offline warm season evaluation. *Journal of Hydrometeorology*, *17*(8), 2293–2313. https://doi.org/10.1175/JHM-D-15-0228.1

Intergovernmental Panel on Climate Change (IPCC) (2019). In H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, & N. M. Weyer (Eds.), *IPCC special report on the ocean and cryosphere in a changing climate*, Cambridge University Press. https://www.ipcc.ch/srocc/

International Permafrost Association (1998). In R. O. van Everdingen (Ed.), *Multi-language glossary of permafrost and related ground-ice terms*. The Arctic Institute of North America, University of Calgary.

Ireson, A. M., Barr, A. G., Johnstone, J. F., Mamet, S. D., Van der Kamp, G., Whitfield, C. J., Michel, N. L., North, R. L., Westbrook, C. J., DeBeer, C., Chun, K. P., Nazemi, A., & Sagin, J. (2015). The changing water cycle: The Boreal Plains ecozone of Western Canada. *Wiley Interdisciplinary Reviews: Water*, *2*(5), 505–521. https://doi.org/10.1002/wat2.1098

Ireson, A. M., Sanchez-Rodriguez, I., Basnet, S., Brauner, H., Bobenic, T., Brannen, R., Elrashidy, M., Braaten, M., Amankwah, S. K., & Barr, A. (2022). Using observed soil moisture to constrain the uncertainty of simulated hydrological fluxes. *Hydrological Processes*, *36*, e14465. https://doi.org/10.1002/hyp.14465

Ismail, M. F., Naz, B. S., Wortmann, M., Disse, M., Bowling, L. C., & Bogacki, W. (2020). Comparison of two model calibration approaches and their influence on future projections under climate change in the Upper Indus Basin. *Climatic Change*, *163*(3), 1227–1246.

Jimenez Cisneros, B. E., Oki, T., Arnell, N. W., Benito, G., Cogley, J. G., Döll, P., Jiang, T., & Mwakalila, S. S. (2014). Freshwater resources. In C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, & L. L. White (Eds.), *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and Sectoral aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel of climate change* (pp. 229–269). Cambridge University Press.

Kouwen, N. (1988). WATFLOOD: A micro-computer based flood forecasting system based on real-time weather radar. *Canadian Water Resources Journal*, *13*(1), 62–77. https://doi.org/10.4296/cwrj1301062

Kouwen, N., Soulis, E. D., Pietroniro, A., Donald, J., & Harrington, R. A. (1993). Grouped response units for distributed hydrologic modeling. *Journal of Water Resources Planning and Management*, *119*(3), 289–305. https://doi.org/10.1061/(ASCE)0733-9496(1993)119:3(289)

Krinner, G., Derksen, C., Essery, R., Flanner, M., Hagemann, S., Clark, M., Hall, A., Rott, H., Brutel-Vuilmet, C., Kim, H., Ménard, C. B., Mudryk, L., Thackeray, C., Wang, L., Arduini, G., Balsamo, G., Bartlett, P., Boike, J., Boone, A., … Zhu, D. (2018). ESM-SnowMIP: Assessing snow models and quantifying snow-related climate feedbacks. *Geoscientific Model Development*, *11*(12), 5027–5049. https://doi.org/10.5194/gmd-11-5027-2018

Krogh, S. A., & Pomeroy, J. W. (2021). Simulating site-scale permafrost hydrology: Sensitivity to modelling decisions and air temperature. *Journal of Hydrology*, *602*, 1–15. https://doi.org/10.1016/j.jhydrol.2021.126771

Lahmers, T. M., Gupta, H., Castro, C. L., Gochis, D. J., Yates, D., Dugger, A., Goodrich, D., & Hazenberg, P. (2019). Enhancing the structure of the WRF-hydro hydrologic model for semiarid environments. *Journal of Hydrometeorology*, *20*(4), 691–714.

Leibowitz, S. G., & Vining, K. C. (2003). Temporal connectivity in a prairie pothole complex. *Wetlands*, *23*(1), 13–25. https://doi.org/10.1672/0277-5212(2003)023[0013:TCIAPP]2.0.CO;2

Letts, M. G., Roulet, N. T., Comer, N. T., Skarupa, M. R., & Verseghy, D. L. (2000). Parametrization of peatland hydraulic properties for the Canadian land surface scheme. *Atmosphere-Ocean*, *38*(1), 141–160. https://doi.org/10.1080/07055900.2000.9649643

Liang, X., Lettenmaier, D. P., Wood, E. F., & Burges, S. J. (1994). A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *Journal of Geophysical Research: Atmospheres*, *99*(D7), 14415–14428.

Liang, X., & Xie, Z. (2001). A new surface runoff parameterization with subgrid-scale soil heterogeneity for land surface models. *Advances in Water Resources*, *24*(9-10), 1173–1193. https://doi.org/10.1016/S0309-1708(01)00032-X

Lindenschmidt, K. E. (2020). *River ice processes and ice flood forecasting: A guide for practitioners and students* (p. 267). Springer International Publishing. https://doi.org/10.1007/978-3-030-28679-8

Lindenschmidt, K.-E., Rokaya, P., Das, A., Li, Z., & Richard, D. (2019). A novel stochastic modelling approach for operational real-time ice-jam flood forecasting. *Journal of Hydrology*, *575*, 381–394. https://doi.org/10.1016/j.jhydrol.2019.05.048

Lindström, G., Pers, C., Rosberg, J., Strömqvist, J., & Arheimer, B. (2010). Development and testing of the HYPE (hydrological predictions for the environment) water quality model for different spatial scales. *Hydrology Research*, *41*(3-4), 295–319. https://doi.org/10.2166/nh.2010.007

Liston, G. E., & Elder, K. (2006). A meteorological distribution system for high-resolution terrestrial modeling (MicroMet). *Journal of Hydrometeorology*, *7*, 217–234. https://doi.org/10.1175/JHM486.1

MacDonald, M. K., Pomeroy, J. W., & Pietroniro, A. (2010). On the importance of sublimation to an alpine snow mass balance in the Canadian Rocky Mountains. *Hydrology and Earth System Sciences*, *14*(7), 1401–1415. https://doi.org/10.5194/hess-14-1401-2010

Marsh, C., Pomeroy, J. W., Spiteri, R., & Wheater, H. (2020). A finite volume blowing snow model for use with variable resolution meshes. *Water Resources Research*, *56*(2), 1–28. https://doi.org/10.1029/2019WR025307

Marsh, C., Pomeroy, J. W., & Wheater, H. (2020). The Canadian hydrological model (CHM) v1.0: A multi-scale, multi-extent, variable-complexity hydrological model - design and overview. *Geoscientific Model Development*, *13*, 225–247. https://doi.org/10.5194/gmd-13-225-2020

McGuire, A. D., Lawrence, D. M., Koven, C., Clein, J. S., Burke, E., Chen, G., Jafarov, E., MacDougall, A. H., Marchenko, S., Nicolsky, D., Peng, S., Rinke, A., Ciais, P., Gouttevin, I., Hayes, D. J., Ji, D., Krinner, G., Moore, J. C., Romanovsky, V., … Zhuang, Q. (2018). Dependence of the evolution of carbon dynamics in the northern permafrost region on the trajectory of climate change. *Proceedings of the National Academy of Sciences*, *115*(15), 3882–3887. https://doi.org/10.1073/pnas.1719903115

Mekonnen, M. A., Wheater, H. S., Ireson, A. M., Spence, C., Davison, B., & Pietroniro, A. (2014). Towards an improved land surface scheme for prairie landscapes. *Journal of Hydrology*, *511*, 105–116. https://doi.org/10.1016/j.jhydrol.2014.01.020

Melton, J. R., Verseghy, D. L., Sospedra-Alfonso, R., & Gruber, S. (2019). Improving permafrost physics in the coupled Canadian land surface scheme (v.3.6.2) and Canadian terrestrial ecosystem model (v.2.1) (CLASS-CTEM). *Geoscientific Model Development*, *12*(10), 4443–4467. https://doi.org/10.5194/gmd-12-4443-2019

Meredith, M., Sommerkorn, M., Cassotta, S., Derksen, C., Ekaykin, A., Hollowed, A., Kofinas, G., Mackintosh, A., Melbourne-Thomas, J., Muelbert, M. M. C., Ottersen, G., Pritchard, H., & Schuur, E. A. G. (2019). Polar regions. In H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, & N. M. Weyer (Eds.), *IPCC special report on the ocean and cryosphere in a changing climate* (pp. 203–320). Cambridge University Press. https://www.ipcc.ch/srocc/chapter/chapter-3-2/

Moore, R. J. (2007). The PDM rainfall-runoff model. *Hydrology and Earth System Sciences*, *11*(1), 483–499. https://doi.org/10.5194/hess-11-483-2007

Morales-Marín, L., Rokaya, P., Sanyal, P., Sereda, J., & Lindenschmidt, K. (2019). Changes in streamflow and water temperature affect fish habitat in the Athabasca River basin in the context of climate change. *Ecological Modelling*, *407*, 108718. https://doi.org/10.1016/j.ecolmodel.2019.108718

Morales-Marín, L. A., Sanyal, P. R., Kadowaki, H., Li, Z., Rokaya, P., & Lindenschmidt, K. E. (2019). A hydrological and water temperature modelling framework to simulate the timing of river freeze-up and ice-cover breakup in large-scale catchments. *Environmental Modelling & Software*, *114*, 49–63. https://doi.org/10.1016/j.envsoft.2019.01.009

Nazemi, A., & Wheater, H. S. (2015a). On inclusion of water resource management in earth system models–part 1: Problem definition and representation of water demand. *Hydrology and Earth System Sciences*, *19*(1), 33–61. https://doi.org/10.5194/hess-19-33-2015

Nazemi, A., & Wheater, H. S. (2015b). On inclusion of water resource management in earth system models–Part 2: Representation of water supply and allocation and opportunities for improved modeling. *Hydrology and Earth System Sciences*, *19*(1), 63–90. https://doi.org/10.5194/hess-19-63-2015

Nicolsky, D. J., Romanovsky, V. E., Alexeev, V. A., & Lawrence, D. M. (2007). Improved modeling of permafrost dynamics in a GCM land-surface scheme. *Geophysical Research Letters*, *34*(8), L08501. https://doi.org/10.1029/2007GL029525

Nijssen, B., O'Donnell, G. M., Lettenmaier, D. P., Lohmann, D., & Wood, E. F. (2001). Predicting the discharge of global rivers. *Journal of Climate*, *14*(15), 3307–3323.

Pan, X., Li, Y., Yu, Q., Shi, X., Yang, D., & Roth, K. (2016). Effects of stratified active layers on high-altitude permafrost warming: A case study on the Qinghai–Tibet plateau. *The Cryosphere*, *10*(4), 1591–1603. https://doi.org/10.5194/tc-10-1591-2016

Pellerin, P., Ritchie, H., Saucier, F. J., Roy, F., Desjardins, S., Valin, M., & Lee, V. (2004). Impact of a two-way coupling between an atmospheric and an ocean-ice model over the Gulf of St. Lawrence. *Monthly Weather Review*, *132*(6), 1379–1398.

Pietroniro, A., Fortin, V., Kouwen, N., Neal, C., Turcotte, R., Davison, B., Verseghy, D., Soulis, E. D., Caldwell, R., Evora, N., & Pellerin, P. (2007). Development of the MESH modelling system for hydrological ensemble forecasting of the Laurentian Great Lakes at the regional scale. *Hydrology and Earth System Sciences*, *11*(4), 1279–1294. https://doi.org/10.5194/hess-11-1279-2007

Pietroniro, A., & Soulis, E. D. (2003). A hydrology modelling framework for the Mackenzie GEWEX programme. *Hydrological Processes*, *17*(3), 673–676. https://doi.org/10.1002/hyp.5104

Pietroniro, A., Soulis, E. D., Snelgrove, K., & Kouwen, N. (2001). A framework for coupling atmospheric and hydrological models. In *Soil-vegetation-atmosphere transfer schemes and large-scale hydrological models. Proceedings of an international symposium, held during the sixth IAHS scientific assembly*, *Maastricht*, *Netherlands, 18–27 July 2001* (pp. 27–34). IAHS Press, https://www.cabdirect.org/cabdirect/abstract/20013152561

Pokhrel, Y., Hanasaki, N., Koirala, S., Cho, J., Yeh, P. J. F., Kim, H., Kanae, S., & Oki, T. (2012). Incorporating anthropogenic water regulation modules into a land surface model. *Journal of Hydrometeorology*, *13*(1), 255–269. https://doi.org/10.1175/JHM-D-11-013.1

Pomeroy, J. W., Fang, X., & Marks, D. G. (2016). The cold rain-on-snow event of June 2013 in the Canadian Rockies - characteristics and diagnosis. *Hydrological Processes*, *30*, 2899–2914. https://doi.org/10.1002/hyp.10905

Pomeroy, J. W., & Gray, D. M. (1990). Saltation of snow. *Water Resources Research*, *26*(7), 1583–1594. https://doi.org/10.1029/WR026i007p01583

Pomeroy, J. W., & Gray, D. M. (1995). *Snowcover: Accumulation, relocation and management*. *NHRI Science Report No. 7* (pp. 1–135). Division of Hydrology, University of Saskatchewan.

Pomeroy, J. W., Gray, D. M., Brown, T., Hedstrom, N. R., Quinton, W. L., Granger, R. J., & Carey, S. K. (2007). The cold regions hydrological model: A platform for basing process representation and model structure on physical evidence. *Hydrological Processes*, *21*, 2650–2667.

Pomeroy, J. W., Gray, D. M., & Landine, P. G. (1993). The prairie blowing snow model: Characteristics, validation, operation. *Journal of Hydrology*, *144*(1-4), 165–192. https://doi.org/10.1016/0022-1694(93)90171-5

Pomeroy, J. W., Gray, D. M., Shook, K. R., Toth, B., Essery, R. L. H., Pietroniro, A., & Hedstrom, N. (1998). An evaluation of snow accumulation and ablation processes for land surface modelling. *Hydrological Processes*, *12*(15), 2339–2367. https://doi.org/10.1002/(SICI)1099-1085(199812)12:15%3C2339::AID-HYP800%3E3.0.CO;2-L

Pomeroy, J. W., & Li, L. (2000). Prairie and arctic areal snow cover mass balance using a blowing snow model. *Journal of Geophysical Research: Atmospheres*, *105*(D21), 26619–26634. https://doi.org/10.1029/2000JD900149

Pomeroy, J. W., & Male, D. H. (1992). Steady-state suspension of snow. *Journal of Hydrology*, *136*(1-4), 275–301. https://doi.org/10.1016/0022-1694(92)90015-N

Pradhananga, D., & Pomeroy, J. W. (2022). Diagnosing changes in glacier hydrology from physical principles, using a hydrological model with snow redistribution, sublimation, firnification and energy balance ablation algorithms. *Journal of Hydrology*, *608*, 127545. https://doi.org/10.1016/j.jhydrol.2022.127545

Pradhananga, D., Pomeroy, J. W., Aubry-Wake, C., Munro, D. S., Shea, J., Demuth, M. N., Kirat, N. H., Menounos, B., & Mukherjee, K. (2021). Hydrometeorological, glaciological and geospatial research data from the Peyto glacier Research Basin in the Canadian Rockies. *Earth System Science Data*, *13*(6), 2875–2894. https://doi.org/10.5194/essd-13-2875-2021

Prowse, T. D. (2001). River-ice ecology. I: Hydrologic, geomorphic, and water-quality aspects. *Journal of Cold Regions Engineering*, *15*(1), 1–16. https://doi.org/10.1061/(ASCE)0887-381X(2001)15:1(1)

Qi, J., Wang, L., Zhou, J., Song, L., Li, X., & Zeng, T. (2019). Coupled snow and frozen ground physics improves cold region hydrological simulations: An evaluation at the upper Yangtze River basin (Tibetan plateau). *Journal of Geophysical Research: Atmospheres*, *124*(23), 12985–13004.

Rawls, W. J., Brakensiek, D. L., & Miller, N. (1983). Green-Ampt infiltration parameters from soils data. *Journal of Hydraulic Engineering*, *109*(1), 62–70. https://doi.org/10.1061/(ASCE)0733-9429(1983)109:1(62)

Razavi, S., & Gupta, H. V. (2016a). A new framework for comprehensive, robust, and efficient global sensitivity analysis: 1. Theory. *Water Resources Research*, *52*(1), 423–439. https://doi.org/10.1002/2015WR017558

Razavi, S., & Gupta, H. V. (2016b). A new framework for comprehensive, robust, and efficient global sensitivity analysis: 2. Application. *Water*

Resources Research, *52*(1), 440–455. https://doi.org/10.1002/2015WR017559

Razavi, S., Jakeman, A., Saltelli, A., Prieur, C., Iooss, B., Borgonovo, E., Plischke, E., Piano, S. L., Iwanaga, T., Becker, W., Tarantola, S., Guillaume, J. H. A., Jakeman, J., Gupta, H., Melillo, N., Rabitti, G., Chabridon, V., Duan, Q., & Maier, H. R. (2021). The future of sensitivity analysis: An essential discipline for systems modeling and policy support. *Environmental Modelling & Software*, *137*, 104954. https://doi.org/10.1016/j.envsoft.2020.104954

Razavi, S., Sheikholeslami, R., Gupta, H. V., & Haghnegahdar, A. (2019). VARS-TOOL: A toolbox for comprehensive, efficient, and robust sensitivity and uncertainty analysis. *Environmental Modelling & Software*, *112*, 95–107. https://doi.org/10.1016/j.envsoft.2018.10.005

Rokaya, P., Budhathoki, S., & Lindenschmidt, K.-E. (2018a). Trends in the timing and magnitude of ice-jam floods in Canada. *Scientific Reports*, *8*(1), 5834. https://doi.org/10.1038/s41598-018-24057-z

Rokaya, P., Morales-Marín, L., Bonsal, B., Wheater, H., & Lindenschmidt, K.-E. (2019a). Climatic effects on ice phenology and ice-jam flooding of the Athabasca River in western Canada. *Hydrological Sciences Journal*, *64*(11), 1265–1278. https://doi.org/10.1080/02626667.2019.1638927

Rokaya, P., Morales-Marin, L., & Lindenschmidt, K.-E. (2020a). A physically-based modelling framework for operational forecasting of river ice breakup. *Advances in Water Resources*, *139*, 103554. https://doi.org/10.1016/j.advwatres.2020.103554

Rokaya, P., Peters, D. L., Bonsal, B., Wheater, H., & Lindenschmidt, K.-E. (2019b). Modelling the effects of climate and flow regulation on ice-affected backwater staging in a large northern river. *River Research and Applications*, *35*(6), 587–600. https://doi.org/10.1002/rra.3436

Rokaya, P., Peters, D. L., Elshamy, M., Budhathoki, S., & Lindenschmidt, K. E. (2020b). Impacts of future climate on the hydrology of a northern headwaters basin and its implications for a downstream deltaic ecosystem. *Hydrological Processes*, *34*(7), 1630–1646. https://doi.org/10.1002/hyp.13687

Rokaya, P., Wheater, H., & Lindenschmidt, K.-E. (2018b). Promoting sustainable ice-jam flood management along the Peace River and peace-Athabasca Delta. *Journal of Water Resources Planning and Management*, *145*(1), 04018085. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001021

Rutter, N., Essery, R., Pomeroy, J., Altimir, N., Andreadis, K., Baker, I., Barr, A., Bartlett, P., Boone, A., Deng, H., Douville, H., Dutra, E., Elder, K., Ellis, C., Feng, X., Gelfan, A., Goodbody, A., Gusev, Y., Gustafsson, D., … Yamazaki, T. (2009). Evaluation of forest snow processes models (SnowMIP2). *Journal of Geophysical Research: Atmospheres*, *114*(D6), D06111. https://doi.org/10.1029/2008JD011063

Sapriza-Azuri, G., Gamazo, P., Razavi, S., & Wheater, H. S. (2018). On the appropriate definition of soil profile configuration and initial conditions for land surface–hydrology models in cold regions. *Hydrology and Earth System Sciences*, *22*(6), 3295–3309. https://doi.org/10.5194/hess-22-3295-2018

Schnorbus, M., Werner, A., & Bennett, K. (2014). Impacts of climate change in three hydrologic regimes in British Columbia, Canada. *Hydrological Processes*, *28*(3), 1170–1189.

Schoeneberg, A. T., & Schnorbus, M. A. (2021). *Exploring the strength and limitations of PCIC's CMIP5 hydrologic scenarios* (p. 42). Pacific Climate Impacts Consortium, University of Victoria.

Semenova, O., Vinogradov, Y., Vinogradova, T., & Lebedeva, L. (2014). Simulation of soil profile heat dynamics and their integration into hydrologic modelling in a permafrost zone. *Permafrost and Periglacial Processes*, *25*(4), 257–269.

Shaw, D. A. (2009). *The influence of contributing area on the hydrology of the prairie pothole region of North America* [*Ph.D. Thesis*. Department of Geography and Planning, University of Saskatchewan, Saskatoon, SK, Canada], p. 167.

Shaw, D. A., Pietroniro, A. L., & Martz, L. W. (2013). Topographic analysis for the prairie pothole region of Western Canada. *Hydrological Processes*, *27*(22), 3105–3114. https://doi.org/10.1002/hyp.9409

Shaw, D. A., Vanderkamp, G., Conly, F. M., Pietroniro, A., & Martz, L. (2012). The fill–spill hydrology of prairie wetland complexes during drought and deluge. *Hydrological Processes*, *26*(20), 3147–3156. https://doi.org/10.1002/hyp.8390

Sheikholeslami, R., Razavi, S., Gupta, H. V., Becker, W., & Haghnegahdar, A. (2019). Global sensitivity analysis for high-dimensional problems: How to objectively group factors and measure robustness and convergence while reducing computational cost. *Environmental Modelling & Software*, *111*, 282–299. https://doi.org/10.1016/j.envsoft.2018.09.002

Shook, K., Papalexiou, S., & Pomeroy, J. W. (2021). Quantifying the effects of prairie depressional storage complexes on drainage basin connectivity. *Journal of Hydrology*, *593*, 125846. https://doi.org/10.1016/j.jhydrol.2020.125846

Shook, K., Pomeroy, J. W., Spence, C., & Boychuk, L. (2013). Storage dynamics simulations in prairie wetland hydrology models: Evaluation and parameterization. *Hydrological Processes*, *27*(13), 1875–1889. https://doi.org/10.1002/hyp.9867

Shook, K. R., & Pomeroy, J. W. (2011). Memory effects of depressional storage in northern prairie hydrology. *Hydrological Processes*, *25*(25), 3890–3898. https://doi.org/10.1002/hyp.8381

Snelgrove, K. R. (2002). *Implications of lateral flow generation on land-surface scheme fluxes* [Ph.D. Thesis, University of Waterloo, Waterloo, ON, Canada], p. 290, http://hdl.handle.net/10012/865

Soulis, E. D., Craig, J. R., Fortin, V., & Liu, G. (2011). A simple expression for the bulk field capacity of a sloping soil horizon. *Hydrological Processes*, *25*(1), 112–116. https://doi.org/10.1002/hyp.7827

Soulis, E. D., Snelgrove, K. R., Kouwen, N., Seglenieks, F., & Verseghy, D. L. (2000). Towards closing the vertical water balance in Canadian atmospheric models: Coupling of the land surface scheme CLASS with the distributed hydrological model WATFLOOD. *Atmosphere-Ocean*, *38*(1), 251–269. https://doi.org/10.1080/07055900.2000.9649648

Stadnyk, T. A., MacDonald, M. K., Tefs, A., Déry, S. J., Koenig, K., Gustafsson, D., Isberg, K., Arheimer, B., & Olden, J. D. (2020). Hydrological modeling of freshwater discharge into Hudson Bay using HYPE. *Elementa: Science of the Anthropocene*, *8*, 43. https://doi.org/10.1525/elementa.439

Stewart, R. E., Szeto, K. K., Bonsal, B. R., Hanesiak, J. M., Kochtubajda, B., Li, Y., Thériault, J. M., DeBeer, C. M., Tam, B. Y., Li, Z., Liu, Z., Bruneau, J. A., Duplessis, P., Marinier, S., & Matte, D. (2019). Summary and synthesis of Changing Cold Regions Network (CCRN) research in the interior of western Canada–Part 1: Projected climate and meteorology. *Hydrology and Earth System Sciences*, *23*(8), 3437–3455. https://doi.org/10.5194/hess-23-3437-2019

Tapley, B. D., Watkins, M. M., Flechtner, F., Reigber, C., Bettadpur, S., Rodell, M., Sasgen, I., Famiglietti, J. S., Landerer, F. W., Chambers, D. P., Reager, J. T., Gardner, A. S., Save, H., Ivins, E. R., Swenson, S. C., Boening, C., Dahle, C., Wiese, D. N., Dobslaw, H., … Velicogna, I. (2019). Contributions of GRACE to understanding climate change. *Nature Climate Change*, *9*(5), 358–369. https://doi.org/10.1038/s41558-019-0456-2

Tefs, A. A. G., Stadnyk, T. A., Koenig, K. A., Dery, S. J., Macdonald, M. K., Slota, P., Crawfood, J., & Hamilton, M. (2021). Simulating river regulation and reservoir performance in a continental-scale hydrologic model. *Environmental Modelling & Software*, *141*, 105025. https://doi.org/10.1016/j.envsoft.2021.105025

Tesfa, T. K., Leung, L. R., & Ghan, S. J. (2020). Exploring topography-based methods for downscaling subgrid precipitation for use in earth system models. *Journal of Geophysical Research: Atmospheres*, *125*(5), e2019JD031456. https://doi.org/10.1029/2019JD031456

Van der Kamp, G., & Hayashi, M. (2009). Groundwater-wetland ecosystem interaction in the semiarid glaciated plains of North America.

Hydrogeology Journal, *17*(1), 203–214. https://doi.org/10.1007/s10040-008-0367-1

Verseghy, D. L. (2000). The Canadian land surface scheme (CLASS): Its history and future. *Atmosphere-Ocean*, *38*(1), 1–13. https://doi.org/10.1080/07055900.2000.9649637

Verseghy, D. L. (2012). CLASS–the Canadian land surface scheme (version 3.6). *Environment Canada science and technology branch*. *Technical Report*, *176*, 176.

Verseghy, D. L., Saunders, I. R., Bowers, J. D., Huo, Z., & Bailey, W. G. (2000). Application of the Canadian land surface scheme (CLASS) to the simulation of energy and water fluxes over alpine tundra. *Atmosphere-Ocean*, *38*(1), 37–55. https://doi.org/10.1080/07055900.2000.9649639

Vionnet, V., Marsh, C., Menounos, B., Gascoin, S., Wayand, N., Shea, J., Mukherjee, K., & Pomeroy, J. W. (2021). Multi-scale snowdrift-permitting modelling of mountain snowpack. *The Cryosphere*, *15*(2), 743–769. https://doi.org/10.5194/tc-15-743-2021

Walvoord, M. A., & Kurylyk, B. L. (2016). Hydrologic impacts of thawing permafrost—A review. *Vadose Zone Journal*, *15*(6), vzj2016-01. https://doi.org/10.2136/vzj2016.01.0010

Wang, L., Zhou, J., Qi, J., Sun, L., Yang, K., Tian, L., Lin, Y., Liu, W., Shrestha, M., Xue, Y., Koike, T., Ma, Y., Li, X., Chen, Y., Chen, D., Piao, S., & Lu, H. (2017). Development of a land surface model with coupled snow and frozen soil physics. *Water Resources Research*, *53*(6), 5085–5103. https://doi.org/10.1002/2017WR020451

Wheater, H., & Gober, P. (2013). Water security in the Canadian prairies: Science and management challenges. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *371*(2002), 20120409. https://doi.org/10.1098/rsta.2012.0409

Wicks, J. M., & Bathurst, J. C. (1996). SHESED: A physically based, distributed erosion and sediment yield component for the SHE hydrological modelling system. *Journal of Hydrology*, *175*(1-4), 213–238. https://doi.org/10.1016/S0022-1694(96)80012-6

Woo, M. K. (2008). *Cold region atmospheric and hydrologic studies - the Mackenzie GEWEX experience: Volume 1: Atmospheric dynamics*. Springer-Verlag. https://doi.org/10.1007/978-3-540-73936-4

Woo, M. K. (2012). *Permafrost hydrology* (p. 564). Springer. https://doi.org/10.1007/978-3-642-23462-0

Wood, E. F., Lettenmaier, D. P., & Zartarian, V. G. (1992). A land-surface hydrology parameterization with subgrid variability for general circulation models. *Journal of Geophysical Research: Atmospheres*, *97*(D3), 2717–2728. https://doi.org/10.1029/91JD01786

Wu, Y., Verseghy, D. L., & Melton, J. R. (2016). Integrating peatlands into the coupled Canadian land surface scheme (CLASS) v3. 6 and the Canadian terrestrial ecosystem model (CTEM) v2. 0. *Geoscientific Model Development*, *9*(8), 2639–2663. https://doi.org/10.5194/gmd-9-2639-2016

Xu, X., Tolson, B. A., Li, J., Staebler, R. M., Seglenieks, F., Haghnegahdar, A., & Davison, B. (2015). Assimilation of SMOS soil moisture over the Great Lakes basin. *Remote Sensing of Environment*, *169*, 163–175. https://doi.org/10.1016/j.rse.2015.08.017

Yang, X., Pavelsky, T. M., & Allen, G. H. (2020). The past and future of global river ice. *Nature*, *577*(7788), 69–73. https://doi.org/10.1038/s41586-019-1848-1

Yassin, F., Pomeroy, J., Pietroniro, A., Princz D., & Razavi, S., (n.d.). Water balance analysis of the Saskatchewan River Bain using MESH model. in preparation.

Yassin, F., Razavi, S., Elshamy, M., Davison, B., Sapriza-Azuri, G., & Wheater, H. (2019). Representation and improved parameterization of reservoir operation in hydrological and land-surface models. *Hydrology and Earth System Sciences*, *23*(9), 3735–3764. https://doi.org/10.5194/hess-23-3735-2019

Yassin, F., Razavi, S., Wheater, H., Sapriza-Azuri, G., Davison, B., & Pietroniro, A. (2017). Enhanced identification of a hydrologic model using streamflow and satellite water storage data: A multicriteria sensitivity analysis and optimization approach. *Hydrological Processes*, *31*(19), 3320–3333. https://doi.org/10.1002/hyp.11267

Yearsley, J. (2012). A grid-based approach for simulating stream temperature. *Water Resources Research*, *48*(3), W03506. https://doi.org/10.1029/2011WR011515

Yirdaw, S. Z., Snelgrove, K. R., Seglenieks, F. R., Agboma, C. O., & Soulis, E. D. (2009). Assessment of the WATCLASS hydrological model result of the Mackenzie River basin using the GRACE satellite total water storage measurement. *Hydrological Processes*, *23*(23), 3391–3400. https://doi.org/10.1002/hyp.7450

Zhao, L., & Gray, D. M. (1999). Estimating snowmelt infiltration into frozen soils. *Hydrological Processes*, *13*(12-13), 1827–1842. https://doi.org/10.1002/(SICI)1099-1085(199909)13:12/13%3C1827::AID-HYP896%3E3.0.CO;2-D

How to cite this article: Wheater, H. S., Pomeroy, J. W., Pietroniro, A., Davison, B., Elshamy, M., Yassin, F., Rokaya, P., Fayad, A., Tesemma, Z., Princz, D., Loukili, Y., DeBeer, C. M., Ireson, A. M., Razavi, S., Lindenschmidt, K.-E., Elshorbagy, A., MacDonald, M., Abdelhamed, M., Haghnegahdar, A., & Bahrami, A. (2022). Advances in modelling large river basins in cold regions with Modélisation Environmentale Communautaire—Surface and Hydrology (MESH), the Canadian hydrological land surface scheme. *Hydrological Processes*, *36*(4), e14557. https://doi.org/10.1002/hyp.14557