Evaluating Climate Change Effects on Water Availability for a Proposed Mine in Eastern Canada

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Abstract

A semi-distributed hydrological model was developed to assess climate change effects on water availability for a planned mine in Newfoundland and Labrador, Canada. The model was set up using publicly available topographical and meteorological data. The potential effects of climate change on water availability were evaluated using an ensemble of CMIP6 simulations for the SSP2-4.5 and SSP3-7.0 climate change scenarios. Results show reduced annual peak discharge with earlier timing, increased winter flows from rainfall and mid-winter melts, and decreased summer water availability. These findings emphasize the need for proactive water resource management to support the mine project.

Keywords: Mine water management, hydrological modelling, climate change effects assessment

Introduction

Understanding long-term hydrometeorological conditions is crucial for assessing water resource availability and variability, particularly in the context of mining projects that rely on sustainable water management. Hydrological assessments are essential for mitigating risks associated with water scarcity, flooding, and water quality, all of which can affect operational efficiency and environmental compliance. As the changing climate continues to alter hydrological regimes, robust modelling approaches are essential for predicting future water availability and supporting proactive water resources management.

Hydrological assessment methods for mining projects often rely on lumped conceptual models, which represent an entire catchment as a single unit by averaging spatial characteristics into aggregated parameters. These models, though computationally efficient and requiring relatively low data inputs, are largely dependent on empirical relationships and generalized assumptions (Beven, 2012). While they can provide reasonable estimates under conditions similar to those used for calibration, a reliance on simplified parameterizations limits the model and its applicability to regions with differing climatic, geological, or land-use characteristics (Gupta *et al.*, 2014). Moreover, their limited physical basis hinders their ability to accurately simulate hydrological responses under non-stationary conditions, such as those driven by climate change.

In contrast, fully distributed physically based models provide a more detailed representation of hydrological processes by incorporating spatial heterogeneity at finer resolution. These models offer improved predictive capabilities, particularly under changing climatic conditions, as they rely on parameters with direct physical connections to a location of interest, while explicitly accounting for spatial heterogeneity in hydrological processes (Clark *et al.*, 2017). However, their application is often constrained by extensive data requirements and high computational demands, limiting practical applications in data-scarce environments.

Advancing hydrological modelling for mining projects requires an approach that integrates conceptual and physically based methods in a semi-distributed framework.

Semi-distributed models offer a compromise by representing catchment heterogeneity at a sub-basin or hydrological response unit level while maintaining a balance between computational efficiency and physical realism (Arnold *et al.*, 2012). Additionally, the increasing availability of high-resolution gridded meteorological and topographical datasets provides an opportunity to enhance the accuracy of semi-distributed hydrological models, particularly in remote or ungauged regions (Mizukami *et al.*, 2017).

This study evaluates the potential effects of climate change on water availability for a planned mining project in Newfoundland and Labrador, Canada. To achieve this, a semi-distributed hydrological model was developed to simulate both present and future hydrological conditions in Flora Creek, a natural (unregulated) catchment with a drainage area of 140 km^2 and located near the proposed mine site. Outputs from the semi-distributed hydrological model were then incorporated into a comprehensive mine site water balance and water quality model. Through this modelling framework, the study aims to provide insights into the potential hydrological changes and support sustainable water management strategies for mining operations.

Methods

Flora Creek basin was modelled using a customized version of the HBV-EC model emulated with the Raven Hydrological Modelling Framework version 3.7 (Craig *et al.*, 2020). The Raven HBV-EC model is a semi-distributed hydrological model that is based on hydrological response units (HRUs), each defined by a distinct combination of physical attributes such as land use, vegetation cover, terrain type, soil profile and bedrock geology. The model follows a water balance approach to each HRU in the model domain, ensuring the conservation of mass. The model requires daily precipitation, as well as minimum and maximum air temperature to simulate basin hydrology. Its algorithms integrate both conceptual and physically based parameterizations. The model consists of three components: (i) a snow routine for snow accumulation and snowmelt based on the degree-day method; (ii) a soil routine that controls the proportion of rainwater and snowmelt, which generates excess water after considering soil moisture and evaporation requirements; and (iii) a runoff generation routine consisting of an upper, nonlinear reservoir that represents fast discharge and a lower linear reservoir that represents slow discharge or baseflow (fig. 1).

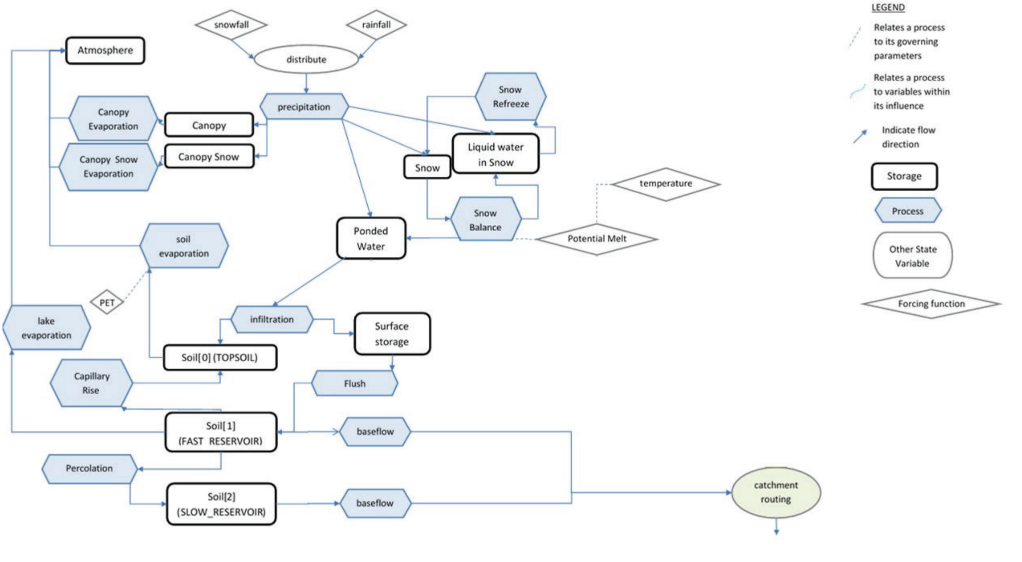

***Figure 1** The schematic of Raven HBV-EC (Craig et al., 2020).*

HRUs were defined in the Flora Creek basin by finding the unique spatial overlay of land cover type, elevation bands, aspect and slope. Land cover data were obtained from the 30m spatial resolution 2020 Land Cover Map of Canada, which is generated by the Canada Centre for Remote Sensing (CCRS). Elevation bands, slope and aspect values were derived from the Canadian Digital Elevation Model (CDEM) at 20m spatial resolution provided by Natural Resources Canada.

Daily minimum and maximum air temperatures to force the Raven HBV-EC model for the Flora Creek basin were obtained from the nearest Environment and Climate Change Canada (ECCC) climate station. Precipitation inputs to the model were derived from a combination of data from the same climate station and the Canadian Precipitation Analysis (CaPA) dataset, which integrates observations from manual and automatic ECCC stations along with the data from the radar network (Fortin *et al.*, 2018). Forward looking projections of daily precipitation and air temperature for the basin were obtained from an ensemble of downscaled and bias adjusted CMIP6 simulations, driven by SSP2-4.5 and SSP3-7.0 emission scenarios (Lavoie *et al.*, 2024). While SSP2-4.5 scenario represents an intermediate greenhouse gas emission pathway, SSP3-7.0 reflects a higher emission scenario, therefore a greater degree of future warming.

A Water Survey of Canada station is located at the outlet of the Flora Creek basin, providing mean daily streamflow observations over the past 10 years, which were utilized in this study for model calibration and validation. Additionally, a nearby snow water equivalent (SWE) record (1983–2016) was used for model verification. Data from this station were obtained from the Canadian historical SWE dataset, which compiles manual and automated SWE observations collected by national, provincial, and territorial agencies, as well as hydropower companies (Vionnet *et al.*, 2021).

Model calibration was conducted by adjusting key parameters related to evapotranspiration, soil properties, snow dynamics, and routing, based on a range of values derived from the literature. The performance of the calibrated model in simulating streamflow was assessed using the Kling-Gupta Efficiency (KGE) metric, optimized through the Dynamically Dimensioned Search (DDS) algorithm (Tolson and Shoemaker, 2007), a global optimization method with a budget of 1,000 iterations. The KGE was selected as the primary evaluation metric due to its ability to overcome the limitations of traditional measures such as the Nash-Sutcliffe Efficiency and R-squared metrics, which primarily focus on reproducing the mean and variance of observed data. The KGE ranges from negative infinity to 1, with a value of 1 indicating perfect agreement between model simulations and observed data.

Results

Simulated streamflow was compared at the outlet of the basin for the calibration (2012–2018) and validation (2019–2022) periods (fig. 2). The KGE statistic was above 0.8 over both calibration and validation periods, which suggests that the model is sufficiently reliable in generating representative hydrographs for the Flora Creek basin.

Good agreement between simulated and observed snow water equivalent (SWE) (fig. 3) demonstrates that the model performs sufficiently well in capturing snow accumulation and ablation magnitude and timing. This is particularly promising given that snowmelt runoff largely dominates the streamflow regime at the study basin. Taken together, the model developed for the Flora Creek basin adequately simulates the natural streamflow conditions in the region, along with key hydrological processes such as snowmelt, sublimation and runoff generation. Accordingly, the results also suggest the model is well suited for analysing the future hydrological conditions and can be reliably integrated into the broader mine site water balance and water quality model.

Compared to present climate conditions (defined here as 2003–2023), mean annual temperature is projected to rise across all future periods, with more pronounced warming under SSP3-7.0 (tab. 1). By the 2060–2080 period, both SSP2-4.5 and SSP3-7.0 scenarios suggest that mean annual temperature are

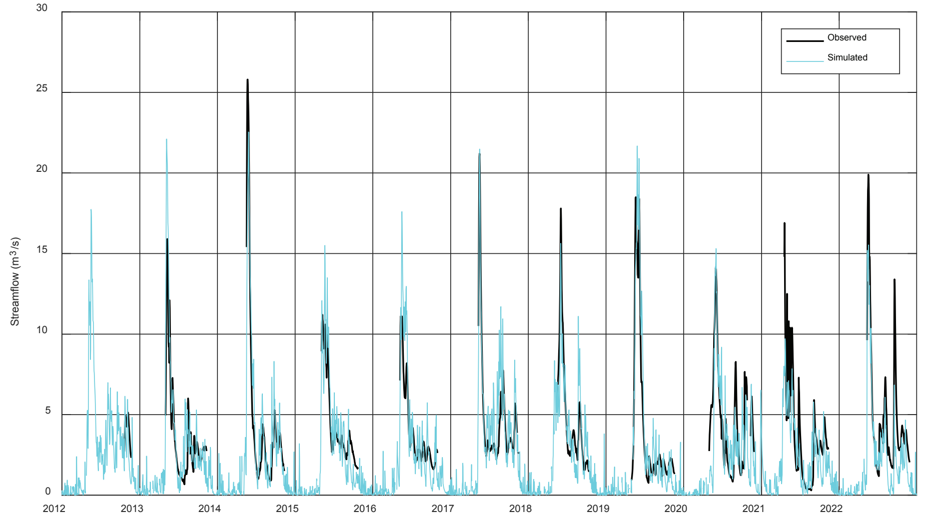

***Figure 2** Raven HBV-EC model performance in simulating Flora Creek streamflow.*

expected to surpass the freezing point, marking a shift in climatic conditions. By the end of this century, mean annual temperature is projected to increase by 3.4 °C under SSP2-4.5, whereas SSP3-7.0 predicts a much more substantial rise of 7.3 °C.

In addition to rising temperatures, mean annual precipitation is projected to increase under both scenarios (tab. 1). Relative to the present climate, precipitation is projected to increase by 5–8% by 2040–2060 and by 12–16% by the end of the century. However, snowfall as a proportion of total precipitation decreases in the future, reflecting the effect of rising temperatures. Under SSP2-4.5, snowfall declines from 394 mm (42% of total precipitation) under present climate conditions to 328 mm (32%) by the late century. This decrease is even more pronounced under SSP3-7.0, where

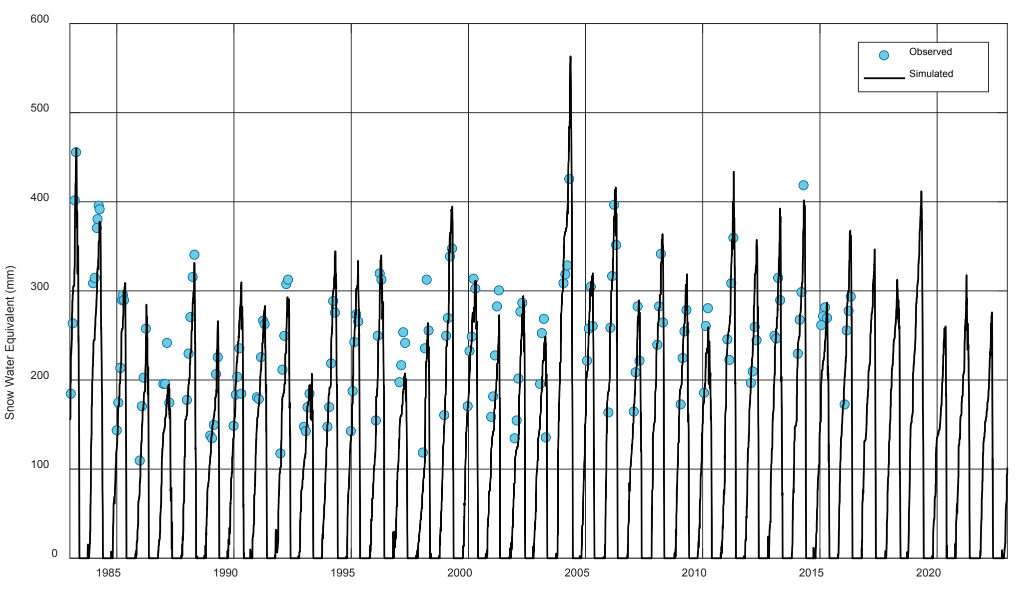

***Figure 3** Comparison of simulated and observed snow water equivalent (SWE).*

Table 3 Mean annual temperature, precipitation and snowfall-rainfall partitioning in precipitation for the present and future simulation periods under SSP2-4.5 and SSP3-7.0 scenarios.

Climate Variable (Annual Mean)	Present (2003–2023)	2040–2060		2060–2080		2080–2100	
		SSP2–4.5	SSP3–7.0	SSP2–4.5	SSP3–7.0	SSP2–4.5	SSP3–7.0
Temperature (°C)	-2.2	-0.3	2.2	0.4	3.6	1.2	5.1
Precipitation (mm)	931	979	1007	1010	1046	1039	1084
Rainfall (mm)	537	633	717	672	786	711	851
Snowfall (mm)	394	346	290	338	260	328	233

snowfall is projected to drop to 21% of total precipitation by 2080–2100, highlighting a stronger shift toward a rainfall dominated precipitation pattern.

Under present climate conditions, the annual peak snow water equivalent (SWE) occurs in April, reaching approximately 260 mm (fig 4). Both SSP2-4.5 and SSP3-7.0 scenarios project a decline in peak snow accumulation over time, with a more pronounced reduction under the higher-emission SSP3-7.0 scenario. By 2040–2060, peak SWE under SSP3-7.0 is projected to decline by nearly 50%, reaching approximately 130 mm, whereas under SSP2-4.5, it is expected to remain above 150 mm throughout the simulation period.

In addition to declining SWE, the timing of peak snow accumulation is expected to shift earlier in the year (fig. 4). Under SSP3-7.0, this shift becomes evident as early as 2040–2060, with peak SWE occurring one month earlier than in the present climate. The shift towards earlier peak SWE is more gradual under the SSP2-4.5 scenario, reflecting a less pronounced but still notable effect of warming temperatures (tab. 1). Furthermore, the duration of the snow-covered period is projected to shorten due to delayed accumulation in the fall and earlier melt in the spring. This reduction in seasonal snow cover is particularly pronounced under SSP3-7.0, emphasizing the greater effect of higher emissions on seasonal snow dynamics.

Projected changes in SWE have direct implications for runoff generation and overall basin yield (fig. 5). Both climate change scenarios considered here project a decline in peak yield, with SSP3-7.0 exhibiting a sharper decrease. By 2040–2060, peak yield is expected to decrease by nearly 40% under SSP3-7.0 and shift about a month earlier in the year, which is consistent with the changes in projected snow accumulation (fig. 4). Winter and early-spring flows are projected to increase under both scenarios due to enhanced rainfall and mid-winter melt events, which contribute to greater

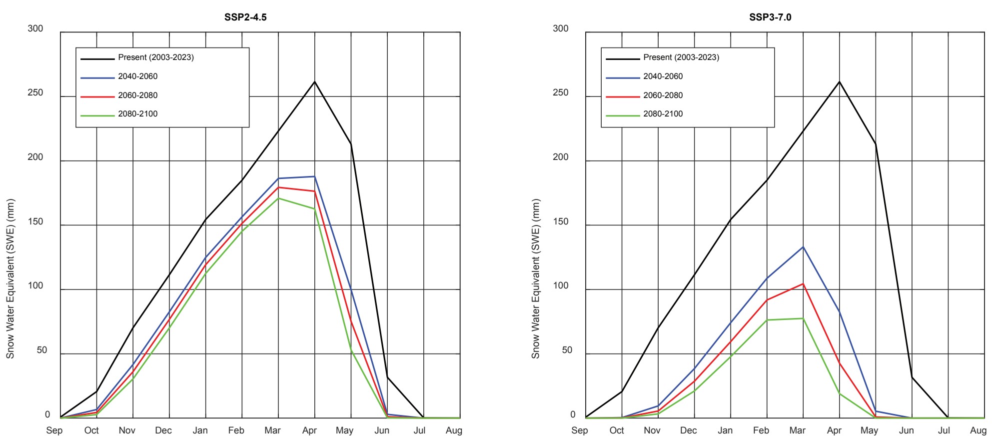

Figure 4 Simulated snow water equivalent (SWE) under present and future climate conditions for SSP2-4.5 and SSP3-7.0 scenarios.

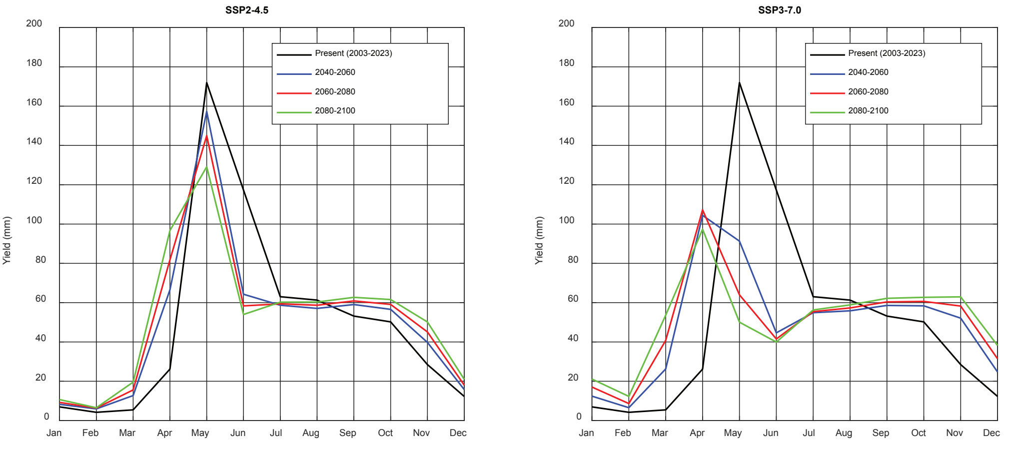

***Figure 5** Simulated basin yield under present and future climate conditions for SSP2-4.5 and SSP3-7.0 scenarios.*

runoff outside the typical snowmelt season. Conversely, summer water availability is projected to decrease by 20–40% depending on the emission scenario and projection period (fig. 5). This reduction is governed by a combination of lower snowpack levels, earlier melting, and higher evapotranspiration rates resulting from warmer temperatures.

Conclusions

The findings of this study underscore the critical need for proactive and strategic water resource management for the planned mine project considering projected climate change effects. More frequent mid-winter melt events and reduced peak snowmelt-driven flows may necessitate modifications to mine water storage infrastructure and their operational procedures, while declining summer water availability could threaten the consistency of water availability for mining operations. These hydrological changes can have direct effects on water quality, as lower flows are expected to reduce the amount dilution, resulting in higher concentrations of contaminants. The severity of these effects will depend on future warming trends, with SSP3-7.0 representing a worst-case scenario and SSP2-4.5 depicting a moderate yet still consequential shift. These scenarios provide a plausible range of potential hydrological changes that mine operators need to consider in long-term water management planning. Ensuring operational efficiency and environmental compliance while minimizing risks associated with fluctuating water resources will require adaptive strategies, including optimizing water storage systems to ensure adequate supply during drier months and improving runoff management practices during wetter months to prevent flooding or excessive runoff. Such proactive actions will be essential not only for ensuring the long-term sustainability of mining operations but also for minimizing the potential environmental and operational disruptions caused by climate variability.

The semi-distributed modelling approach adopted in this study effectively combines both conceptual and physically based methods, resulting in a robust and computationally efficient tool for assessing water availability and managing water-related risks in the mining industry. The inclusion of physical realism within the modelling framework, along with the use of publicly available topographical and meteorological data, enhances its applicability to other mine sites in the region while supporting regulatory compliance.

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