Research papers

Impacts of severe land use changes on the hydrology of snow dominated catchments in southern Quebec

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ABSTRACT

The present study evaluates the hydrological response to severe land use changes using the distributed physically-based hydrological model HYDROTEL over 89 catchments in Eastern North America. Additionally, two catchments were selected to assess the impacts on past extreme flood events. Streamflow simulations were generated using three regional climate simulations from the Canadian Regional Climate Model version 5 (CRCM5) for the 1986–2015 period. The simulations were based on current land use (EVAL) and two extreme land use scenarios with only grass (GRASS) and only forest (FOREST) land use. The FOREST and GRASS simulations include the feedback of land-use to climate. The Multivariate Bias Correction (MBCn) algorithm was applied to correct biases in EVAL simulation, with the same coefficients used for GRASS and FOREST simulations to ensure a consistent climate baseline and maintain the spread of the simulations. HYDROTEL's land-use inputs were adjusted to match those from the CRCM5 simulations. The results indicated significant changes in both the timing and magnitude of spring peak flows associated with snowmelt: the FOREST scenario showed earlier, reduced peak flows, while the GRASS scenario led to delayed, larger peaks. Additionally, the catchments were categorized by size-large (>1000 km²), medium (500–1000 km²), and small (<500 km²)-to evaluate size-related impacts. A model comparison was conducted between HYDROTEL and the physically-based distributed model WaSiM on two diverse catchments, revealing that HYDROTEL demonstrated higher sensitivity to snowmelt and accumulation processes (because of its multi-land use snow model structure), while WaSiM showed greater sensitivity to evapotranspiration (due to its Richards-equation-based soil module). Finally, it was found that the RCM-simulated land use-climate feedback is considerably more important than the hydrological model land-use change effect on the spring flood modification.

1. Introduction

Anthropogenic activities have not only impacted the Earth's climate over the last decades, but they have also led to land use changes through agriculture, deforestation or afforestation, and urbanization (Khadka et al., 2024; Mitiku et al., 2023). At the catchment level, land use changes play an important role in different spatial and temporal processes that drive streamflow production. Among them, infiltration rates, evapotranspiration, and soil moisture are some of the hydrometeorological processes and catchment conditions that can directly influence

hydrological regimes (Öztürk et al., 2013; Parmesan et al., 2022; Sleeter et al., 2018).

Different studies have shown that land use changes can influence hydrological and climatic processes (Bosch and Hewlett, 1982; Brown et al., 2005; Li et al., 2021). For example, Li et al. (2021) showed that the average annual evapotranspiration was closely related to land-use types in an eastern China river catchment, with higher evapotranspiration magnitudes in forest compared to grasslands, croplands, and wetlands. This is in line with the study presented by Yang et al. (2015), where temporal variations of evapotranspiration in the North American east

coast were clearly seen in regions with severe land use conversions. The impacts of land use changes on snow accumulation and snowmelt have also been evaluated at the catchment scale (Szczypta et al., 2015). Szczypta et al. (2015) showed that reforestation had moderate impacts on the snow cover duration. This impact is expected to arise from the shading effect of trees on the snow surface radiation balance (Szczypta et al., 2015). Similarly, a study over the Great Lakes (northern United States of America and Southern Canada) presented by Mao and Cherkauer (2009) showed that the presence of a canopy during the winter reduced the snow cover through interception and limited solar radiation penetration, which in turn retarded the melt of the snowpack and the likelihood of infiltration. The grasslands, wooded grasslands, and cropland areas showed higher spring total runoffs because of their lower evapotranspiration losses and the more rapid loss of snow cover, with grassland showing the highest runoffs (Mao and Cherkauer, 2009). Using in situ historical datasets and remote sensing data at larger scales, Bright et al. (2017) showed that forestation led to annual cooling in many regions around the world, which is in line with the analysis presented by Li et al. (2015) showing clear cooling in the tropics and warming in the higher latitudes. In snow dominated regions, the interactions between evapotranspiration and land-use changes can directly impact the snowmelt and accumulation processes. As described in various studies, an increased density of vegetation at higher latitudes can lead to decreased albedo and enhanced energy absorption by the vegetation, which results in earlier snowmelt (Kropp et al. 2022; Perugini et al.2017). Consequently, this can impact streamflow levels due to potentially longer snow-free periods and earlier onset of evapotranspiration (Fang & Pomeroy 2023, Jia et al. 2019).

The literature shows that forestation and forest protection strategies are often suggested as a flood regulation measure (Dadson et al., 2017; Hurtado-Pidal et al., 2022; Seddon et al., 2020). Different analyses have been proposed to assess the potential impacts of forestation on flooding events. Hurtado-Pidal et al., 2022 evaluated the impact of forestation in a tropical catchment by simulating flood events with a physically-based and distributed hydrological model under different land use parameterizations. The results showed that the location of the forestation and deforestation within the studied catchment had a large influence in flood production. Following a similar approach, Mitiku et al. (2023) coupled the SWAT distributed hydrological model with observed and projected land use conditions, showing the potential increase of flooding events in an Ethiopian catchment. Additionally, it was shown that the effects of climate change had a higher influence in increasing peak events compared to that of the land use changes. Mangi et al., (2022) coupled land use changes extracted from Landsat imagery with the SWAT model over a mountainous catchment, showing that changes from forest to agriculture fields led to runoff increases. Using a scenario-based approach Martin et al., (2017) evaluated the combined effects of land and climate changes in a catchment in North Carolina, showing that changing from forest to urban areas amplified the impacts of climate change. Recently, Khadka et al., (2024) evaluated the impacts of climate and land use changes on droughts projections in Thailand by combining climate change projections with observed land use changes in the region. The results showed, in line with Martin et al., (2017) and Mitiku et al., (2023) that the effects of climate change were different when land use changes were included. In summary, prior studies show mixed conclusions regarding land use impact on floods, partly due to differing methodologies. Notably, few studies have explicitly accounted for land-use–climate feedback mechanisms. This gap in understanding integrated land–climate interactions limit our ability to attribute hydrological changes to land use versus climate influence.

In contrast with the previous conclusions, other studies have highlighted that land use can have a larger influence in the timing and magnitudes of certain flood events and other relevant processes, such as soil moisture and evapotranspiration (Bathurst et al., 2020; Quilbé et al. 2008; Soulsby et al., 2017). Over a snow-dominated North American catchment, Lavigne et al. (2004) proposed and assessed a new integrated

framework, called GIBSI, that combined different distributed modelling modules to simulate hydrological processes and various management systems (i.e., land use and reservoir management). The GIBSI framework uses HYDROTEL as the hydrological model. Their analyses confirmed the predictive capacity of the proposed integrated modelling framework by simulating the historical land and hydrologic evolution of a snow-dominated catchment. Using the same framework, Quilbé et al. 2008 evaluated the hydrological effects of historical and future land use evolution. Their results showed that the historical changes from forest to agriculture fields, resulted in increased precipitation and runoff. Soulsby et al., 2017 evaluated the influence of forest cover in extreme flood events that occurred in a catchment in the United Kingdom. Their analysis revealed that for the most extreme flood events, the expected buffering effect of the forest was surpassed. In other words, the level of influence of land use changes was different depending on the type of flood event. Similarly, Bathurst et al., (2020) evaluated the effects of afforestation in four contrasting field sites. In line with Soulsby et al., 2017, it was observed that forests can mitigate the magnitude of certain flood events (small and medium rain-runoff events). However, during the most extreme flooding events, the mitigating effects of forests decreased.

The different studies assessing the effects of land use changes on floods revealed contrasting conclusions. Some studies showed a limited impact of land use changes, while others highlighted that land use changes (e.g., forestation) can be used to deal with flooding events. These contrasting recommendations can be due to the varied methodologies proposed to evaluate the potential effects of land use on hydrology. Furthermore, we have yet to deepen our understanding of the land-climate interactions when it comes to assessing the impacts of land uses changes, to further be able to attribute the contributions of land use changes and climate changes to the resulting hydrological changes.

The aim of this study is to evaluate the effects of severe land use changes on hydrology by integrating the complex land-climate interactions. Here, 'severe land use changes' refers to extreme hypothetical scenarios of full afforestation versus complete deforestation (grassland conversion), implemented via climate model simulations In other words, this study will analyze the climatic effects of severe land use changes and the hydrological response of the observed climate-land interactions.

2. Study area and data

2.1. Studied catchments

A set of 89 catchments located in the Canadian province of Quebec, in Eastern North America, were studied. As observed in the left panel of Fig. 1, all catchments are in the southern part of Quebec near the limits with the contiguous United States (two catchments, the Richelieu and Châteauguay, are highlighted with bold outlines in Fig. 1 for detailed analysis). This region is located in a humid continental climate with mild and hot summers according to the Köppen-Geiger climate classification (Kottek et al., 2006) and a marked seasonality. The right panels show the mean annual temperature, total precipitation, and maximum snow depth maps extracted from the ERA5 reanalysis (Hersbach et al., 2020) for the 1986–2015 time period. The mean annual temperatures range from about 5 to 7 °C with a slight warm gradient towards southern catchments, and the mean total annual precipitation values vary from less than 1000 mm to 1200 mm per year.

2.2. Observed and simulated data

Climatic and hydrometric time series of historical data were used at the daily time step for each catchment. Daily total precipitation, minimum and maximum temperature series issued from the ERA5 Reanalysis dataset were first used to calibrate and validate the hydrological model.
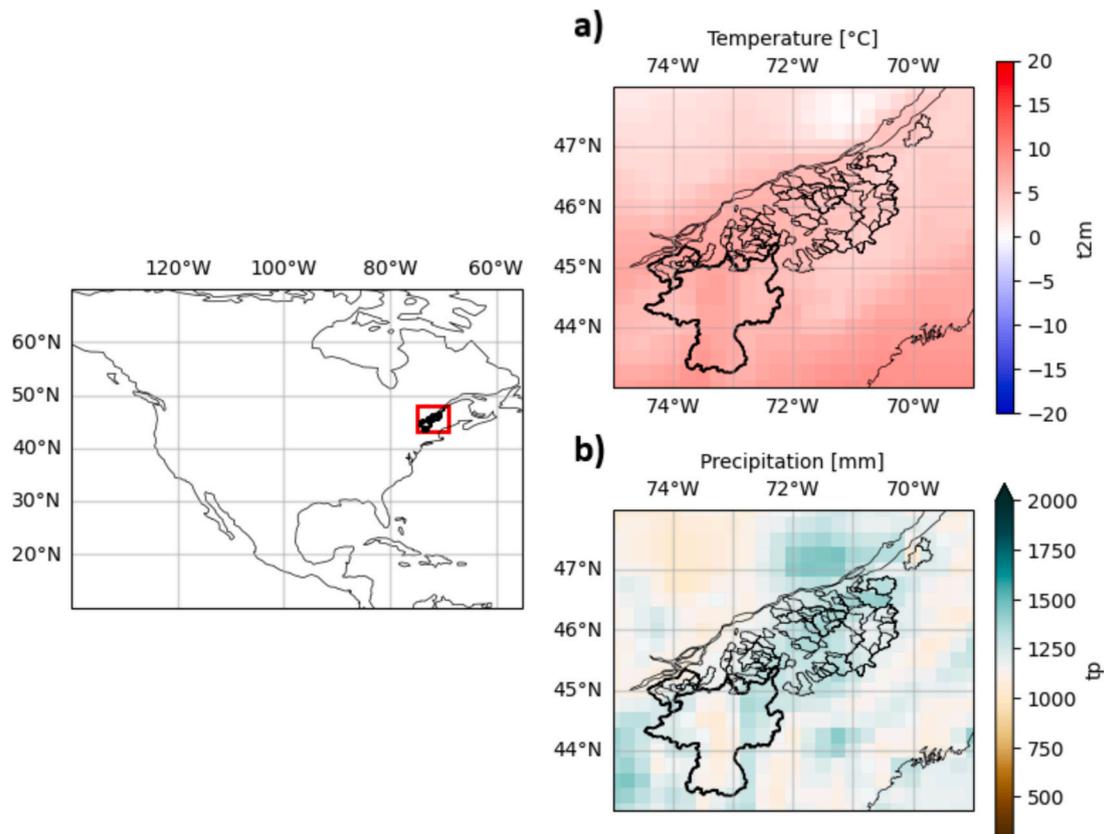
Fig. 1. Locations of the 89 study catchments and their mean annual climatology estimated from the ERA5 reanalysis. The right panels show the mean annual temperature (panel a) and mean total annual precipitation (panel b) over the study area. Two southern catchments selected for further analysis are identified with bold outlines.

The hydrometric data used for this process were all provided by Quebec's Direction principale de l'expertise hydrique (DPEH) and cover the period of 1961–2018. For all 89 selected catchments at least 25 years of streamflow records were available.

2.2.1. ERA5 reanalysis

ERA5 is the fifth generation of atmospheric reanalysis from the European Centre for Medium-Range Weather Forecasts (ECMWF; Hersbach et al., 2020). This reanalysis is available from 1940 to present and it has a horizontal resolution of 0.25° at an hourly time step. This dataset has been used in the study area for different studies (Martel et al., 2024a; Martel et al., 2024b), and it has shown a good performance over North America (Tarek et al., 2020). In addition to the previous satisfactory performance, the use of this dataset allows having continuous climatological series for all catchments considered in the study. While ERA5 data have shown good performance in the region (Tarek et al., 2020), its ~ 25 km grid resolution is relatively coarse for small catchments, which could smooth local variability. We acknowledge this as a limitation, though model calibration helps to partially mitigate this issue.

2.2.2. Regional climate simulations

Three regional climate model simulations produced with the Canadian Regional Climate Model version 5 (CRCM5; Martynov et al., 2013; Separovic et al., 2012) were used in this study. All simulations were driven by the ERA-Interim reanalysis (Dee et al., 2011). These CRCM5 simulations are described and evaluated in the model intercomparison study presented by Asselin et al. (2022). All simulations cover the North American (NAM) domain at a 0.44° (50 km) horizontal resolution with a 20-minute time step for the period of 1979–2015. As highlighted by Asselin et al. (2022), a 7-year spin-up was considered. Thus, all following analyses were performed over the 1986–2015 period. The

daily precipitation, minimum and maximum temperatures issued from the CRCM5 simulations were aggregated at a daily time step and post-processed to be later combined with the HYDROTEL model (described in section 3.2) to obtain the CRCM5-driven streamflow simulations for each catchment.

In terms of land use and cover, all simulations were coupled with the Canadian Land Surface Scheme (CLASS; Verseghy,1991; Verseghy et al., 1993) version 3.5c. All three simulations (hereafter referred to as CRCM5-CLASS simulations) share the same configuration except for their land uses, as displayed in the vegetation fractions of Fig. 2. From left to right, Fig. 2 shows in each column the vegetation fraction (%) of broadleaf trees, needleleaf trees, and grass of the three simulations, respectively named EVAL, FOREST and GRASS. Beyond differences in vegetation fractions, the CRCM5-CLASS simulations also differ in their biophysical parameterization of vegetation types. Each land-cover category (broadleaf, needleleaf, grass) in CLASS v3.5c has distinct properties, such as albedo, leaf-area index, root depth, stomatal resistance, and aerodynamic roughness length (see Asselin et al., 2022, Table 2), which directly affect surface energy balance and evapotranspiration. These differences in land cover feed directly into the hydrological model affecting hydrological processes (e.g., infiltration, potential and actual evapotranspiration, as well as snow melt and accumulation) and model response to land-use scenarios.

The first simulation, referred to as EVAL (first column), consists of a realistic land use representation and serves as the control simulation. The second simulation, referred to as FOREST, represents the maximum tree cover over the regions covered by both broadleaf and needleleaf forests from the EVAL simulation and has no grass land use. The third simulation, referred to as GRASS, replaces all vegetation by grass cover. Overall, the EVAL maps (first column) show that the catchments are mainly characterized by forests, notably broadleaf. The three
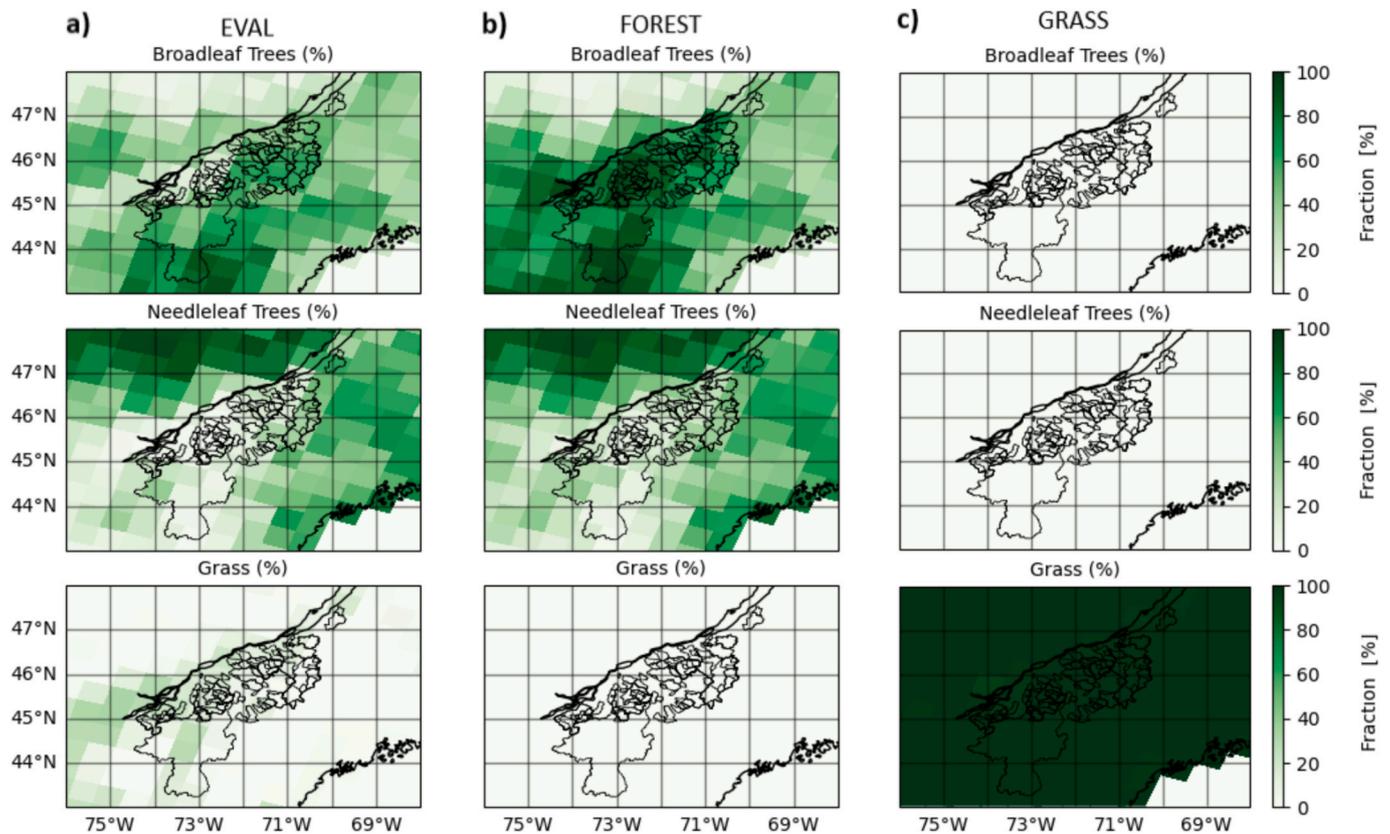
Fig. 2. Vegetation fraction (%) of each CRCM5-CLASS simulation. Column a) refers to the EVAL simulation, column b) refers to the FOREST simulation and column c) refers to the GRASS simulation.

simulations were produced following the European LUCAS project's protocol and were involved in a comparison of the impact of afforestation (GRASS) and reforestation (FOREST) results from different RCMs over a European domain and a North-American domain (Asselin et al., 2022).

3. Methodology

The methodology comprises four main stages that allow evaluating the hydrological impacts of severe land use changes as simulated by three CRCM5-CLASS simulations. First, the precipitation and temperature series issued from the three CRCM5-CLASS simulations, namely EVAL, GRASS, and FOREST, are extracted for each catchment and aggregated at the daily scale. Then, the daily series of precipitation, minimum and maximum temperatures are bias-corrected using the Multivariate Bias Correction (MBCn) method from Cannon (2018) with the ERA5 reanalysis as the reference dataset. After bias-correction, the three CRCM5-CLASS simulations are coupled with a calibrated semi-distributed hydrological model. Finally, four flood indices are estimated from the three hydrological simulations. The models, methods and analyses used in this study are described in detail in the following sections.

3.1. Bias-Correction of climate simulations

The MBCn algorithm involves multiple iterations of rotating the multivariable matrix of climate data using random orthogonal functions and performing quantile mapping on the marginal distributions of the rotated variables. This process continues until the distributions of the simulated and observed climate data align. The advantage of the MBCn algorithm is that it accounts for the interdependence of climate variables while preserving trends in decadal and multi-decadal analyses.

To apply the MBCn method to the FOREST and GRASS datasets, which include precipitation and maximum and minimum temperatures, we first computed the monthly bias coefficients from the EVAL simulations for the period 1986–2015. These coefficients were then applied to the FOREST and GRASS datasets. This approach assumes that climate-model biases are consistent across land-use scenarios. It follows the same rationale as bias correction in climate change studies, where the bias estimated between a simulated baseline and a reference dataset is applied to future simulations. Similarly, we assumed that the biases of the climate simulation under the EVAL scenario, which represents current land cover, can be transferred to the extreme land-use scenarios (FOREST and GRASS). This preserves the relative differences among scenarios, which is essential for our comparison. However, it also implies that any bias in extremes (e.g., precipitation intensity) present in EVAL is carried over to FOREST and GRASS. As a result, while this method highlights scenario contrasts, it may slightly underestimate or overestimate some metrics in the alternative land-use simulations.. An important limitation of our approach is the resolution mismatch between the ERA5 reanalysis (0.25°, ~25 km) used as the reference dataset and the CRCM5 simulations (0.44°, ~50 km) that were bias-corrected. Because ERA5 resolves finer-scale variability than CRCM5, especially for precipitation and snow processes, the bias correction aligns CRCM5 outputs with a reference field that contains sub-grid variability not explicitly represented in CRCM5. This discrepancy may lead to partial adjustments that smooth local-scale extremes or misrepresent their spatial distribution, particularly in smaller basins where local processes are critical. While the correction improves overall consistency between datasets, it introduces uncertainty regarding the extent to which extremes and variability are realistically captured in the corrected CRCM5 outputs. In addition, the climate forcing resolutions (ERA5: ~25 km; CRCM5: ~50 km) are much coarser than the scale of many catchments. We used these datasets at their native resolution to ensure consistency

with the climate simulations. This likely smooths sub-catchment variability and could reduce the model's ability to capture very localized extremes in smaller basins. We acknowledge this as a limitation of our modeling approach.

3.2. Hydrological models

3.2.1. The HYDROTEL semi-distributed hydrological model

The HYDROTEL model is a semi-distributed and partially physically-based hydrological model. One particularity of this hydrological model is that it allows choosing from different sub-models to simulate the main hydrological processes with different algorithms. The user can select from different sub-models to simulate snow accumulation and snow-melt, potential evapotranspiration (PET), flow on subcatchments surface, channel routing, and the vertical water budget (Fortin et al., 2001a). For this study, the selected PET formulation is the Hydro-Québec formulation (Fortin, 2000), and the selected snow model is a modified degree-day (Turcotte et al., 2007) that estimates the daily evolution of the snowpack. The vertical water balance is estimated with a three-layer soil model, the flow on subcatchments surface scheme is a geomorphological hydrograph based on the kinematic wave approximation, and the channel routing scheme is based on the kinematic wave equation. Overall, with the selected modules, the hydrological model has a total of 27 parameters to be calibrated (Fortin et al., 2001b). Based on the recommendations of Turcotte et al. (2007), 11 parameters were calibrated and the remaining 16 were fixed based on recommended values (see Table SII, Supplementary material II, for model parameters). Different studies have used these fixed and calibrated parameters for the reconstruction of historical daily flows (Martel et al. 2023), flood frequency analysis (Martel et al. 2024), and hydrological models weighting (Castañeda-González et al., 2023), supporting the use of the same calibration approach in this study. The description of all calibrated and fixed parameters are provided in Supplementary Material I. This process was performed using the Dynamically Dimensioned Search (DDS) algorithm (Huot et al., 2019; Tolson and Shoemaker, 2007) over the whole 1979–2017 period based on the recommendations of Arsenault et al. (2018) showing that including the whole period in the calibration process results in more robust calibrated parameter sets. The Kling-Gupta Efficiency criterion (KGE; Kling et al., 2012; Knoben et al., 2019) was used as the objective function.

Regarding the input data needed to calibrate HYDROTEL and perform simulations, hydrometeorological and physiographic information is required. The HYDROTEL modules selected for this study require hydrometeorological data consisting of daily time series of total precipitation, and minimum and maximum temperatures. The ERA5 and CRCM5 spatial resolutions (0.25° and 0.44°, respectively) were maintained, and the sub-daily time scales were processed to obtain daily time series for HYDROTEL. The geomorphological information consists of topography, soil type, and land use layers that are provided and processed through PHYSITEL (Rousseau et al., 2011). This GIS-based software prepares all the geomorphological data to be then processed by HYDROTEL using Relatively Homogenous Hydrological units (RHHUs) to divide the study area.

HYDROTEL has been used in the study region for different applications as flood simulations (Lucas-Picher et al., 2015), regionalization methods (Martel et al. 2023), and climate change impact studies (Lucas-Picher et al. 2021,Castaneda-Gonzalez et al., 2023). Additionally, HYDROTEL is applied in an operational context by DPEH for the continuous development of the Hydroclimatic Atlas of Southern Quebec (MELCCFP, 2022). The HYDROTEL model, provided by the DPEH for this study, consists of a fully calibrated model covering 12 large homogeneous regions in southern Quebec. This pre-calibrated HYDROTEL model includes one calibrated set of parameters for the hydrometric stations located north of the Saint-Lawrence River and another for the regions located to the south. In this study, only two of the 12 HYDROTEL regions were used, referred to as the North and South regions in the

following sections, each having its own set of parameters shared between all catchments it contains. When running the hydrological model with outputs from the FOREST and GRASS simulations, the corresponding land use maps are used in the hydrological model. It should be noted that our results are most robust within the studied domain (southern Québec), but may not be directly generalized to other regions with different physiographic or climatic conditions. Thus, while the approach captures broad-scale patterns across a large sample of catchments, fine-scale catchment-specific responses and transferability to other geographic settings should be interpreted with caution

3.2.2. WaSiM

The Water balance Simulation Model (WaSiM, Schulla & Jasper, 2007) is a distributed, process-based model, with a more physically-based soil infiltration scheme (Richards' equation) which can lead to different sensitivities to land cover (e.g., infiltration and soil moisture dynamics). The model incorporates physically based representations of snow accumulation and melt, soil water processes, evapotranspiration, and runoff generation. The model can be configured using gridded input data and supports both raster-based and grid-based simulations. Its snow routine is based on an energy balance approach, making it particularly applicable to snow-influenced basins. Originally developed for alpine environments, WaSiM has been applied in various contexts including flood prediction, land-use change assessments, and climate sensitivity analyses (Schulla and Jasper, 2007).However, WaSiM's snow accumulation/melt routine does not explicitly account for the impact of land covers on snow modeling, which may make it less sensitive to land-use change in winter conditions.

3.2.3. GR7J

To more thoroughly evaluate the hydrological model's influence on the study's results, a modified version of the lumped GR4J model was implemented for two catchments. Further details are presented in the Discussion section.

The GR4J model is a global hydrological model with four parameters, developed by Perrin et al. (2003) for water resource management applications. Its structure is based on two main reservoirs, one simulating runoff production, and the other simulating flow transfer. The model does not account for snow accumulation and melt processes. To integrate these processes, the GR4J model was coupled with the two-parameter CemaNeige model (Valéry et al., 2014). The resulting hydrological model, GR4J-CemaNeige, consists of six parameters and requires daily temperature, precipitation, and evapotranspiration as input data. Based on previous studies (e.g., Arsenault et al., 2018; Troin et al., 2018), the potential evapotranspiration (PET) formulation proposed by Oudin (Oudin et al., 2005) was adopted. To incorporate land cover change sensitivity into a global model such as GR4J-CemaNeige-Oudin, the parameters related to snow modeling were modified, and an additional parameter associated with potential evapotranspiration (PET) was introduced. The resulting 7-parameter GR4J model, hereafter referred to as GR7J, is further described in Supplementary Material I.

3.3. Swapped simulations

A set of two additional simulations, called the "swapped" simulations, were also implemented. Those refer to running the hydrological model with the swapped climate and land use combinations. Swapped FOREST means that the hydrological model setup is FOREST but it is forced with the GRASS climate data, this is termed the Swapped FOREST simulation. Swapped GRASS is the opposite.

This configuration helps investigate the need for coherency between climate and hydrological models in terms of extreme land-use simulations and their corresponding feedbacks to climate. Moreover, swapped simulations can potentially identify the hydrological processes sensitive to extreme land use and their representation within the model, when compared with the normal climate feedback simulations. This is because

the model is run with the same climate feedback but with a different modeling setup. To highlight the sensitivity of the hydrological model to those extreme land-use scenarios, we compared the results with the-WaSiM hydrological mode.

3.4. Flood indices

Four different indices were selected to evaluate and compare the flood peaks over the different land use scenarios. The four flood indices are used on an operational basis in the studied region through the Hydroclimatic Atlas of Southern Quebec (MELCCFP, 2022) to define and evaluate extreme flooding events in the catchments. Each index is defined as follows:

Q1MAXAN: This index consists of the annual maximum daily streamflow (m³/s). This index is calculated for different return periods, namely, 2-,5-,10-,20-, 100-, and 350-year return periods, using the Log-Pearson type III distribution. This index has been normalized by each catchment's mean annual streamflow to facilitate analysis and comparison between different catchments.

Q1MAXWS: This index consists of the winter-spring maximum daily streamflow (m³/s). The months of December through May are considered to estimate the maximum values. This index is calculated for different return periods, namely, 2-,5-,10-,20-, 100-, and 350-year return periods, using the Log-Pearson type III distribution. This index has been normalized by each catchment's mean winter-spring streamflow to facilitate analysis and comparison between different catchments.

Q1MAXSF: This index consists of the summer-fall maximum daily streamflow (m³/s). The months of June through November are considered to estimate the maximum values. This index is calculated for different return periods, namely, 2-,5-,10-,20-, 100-, and 350-year return periods, using the Log-Pearson type III distribution. This index has been normalized by each catchment's mean summer-fall streamflow to facilitate analysis and comparison between different catchments.

DQ1MAXWS: This index consists of the average day of occurrence of the maximum daily streamflow during the winter-spring period. The number of days is estimated from January 1st.

The estimation of return periods for the different indices was carried out by assessing the suitability of the Log-Pearson Type III distribution, selected based on commonly used distributions in the region as described in the Hydroclimatic Atlas of Southern Quebec (MELCCFP, 2022, Castaneda-Gonzalez et al., 2022 and Pouryousefi Markhali, 2023). The distribution parameters were estimated using the maximum likelihood method (MLM), and the goodness of fit was evaluated at the 95 % confidence level for all basins.

3.5. Summary of the methodology

In general, the methodology can be summarized in four main stages, as presented in Fig. 3.
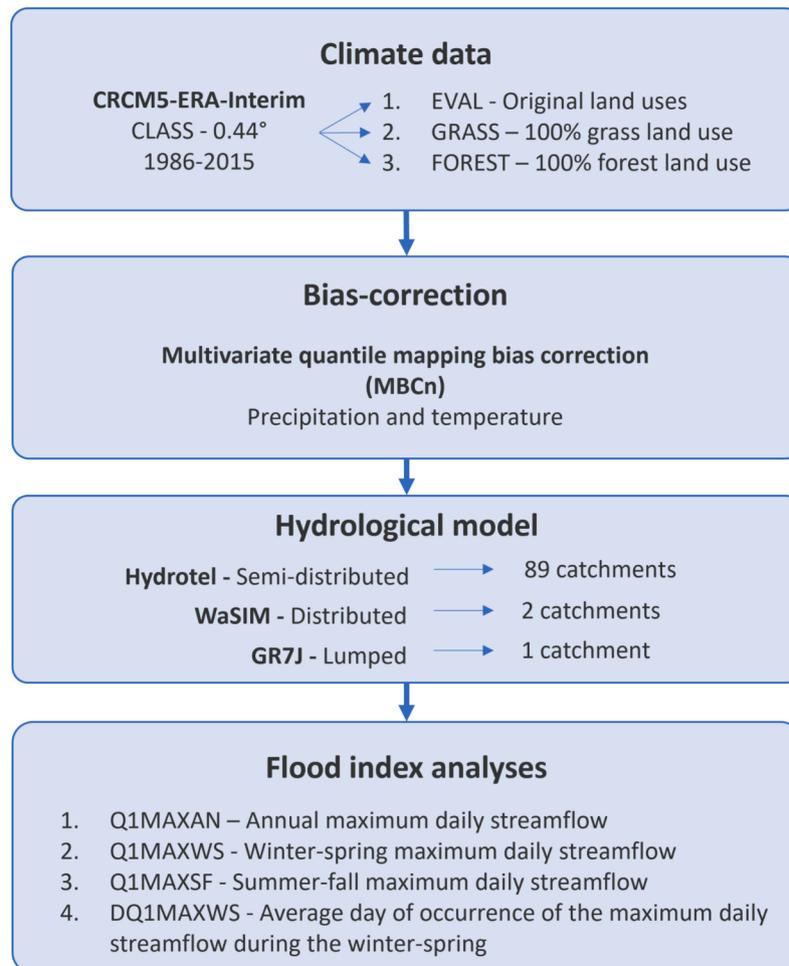

Fig. 3. Summary of the methodology flowchart of the study.

4. Results

4.1. Hydrological model performance

Fig. 4 shows the hydrological model calibration performance of all the catchments. The figure in panel "a" shows the boxplots of the north and south regions, and panel "b" shows the geographical distribution of the KGE values in the study area. The two regions highlighted in red in panel "b" have been defined and used by the DPEH (MELCCFP, 2022) to create the HYDROTEL platforms that were used in this study.

Overall, the 89 catchments display a good hydrological modelling performance with all KGE-values above 0.7. As presented in panel "a", the KGE values in the north region show slightly better performance than those in the south region, with median values of 0.82 and 0.8, respectively. This result is also observed in panel "b", where catchments located in the northern latitudes show generally higher KGEs (in darker blue).

The marginally higher performance in the North may relate to the larger, more natural catchments of those basins. Northern catchments might also have a more snow-dominated regime which HYDROTEL, with its degree-day snow module, handles well, resulting in slightly better fit. In contrast, Southern catchments, which have more varied land use and possibly more human impact, showed marginally lower KGE. However, the difference is small, and overall performance is good in both regions.

4.2. Impact of land use change on CRCM5 climatology

Fig. 5 shows the mean annual climatology of the three bias-corrected CRCM5-CLASS simulations (i.e., EVAL, FOREST and GRASS) over the north and south regions presented in panel "a" and "b", respectively. For each region, three climate variables that were used to produce the hydrological simulations are presented. From top to bottom, mean monthly precipitation, mean daily maximum and minimum temperatures averaged over the 1986–2015 reference period are shown.

In terms of precipitation, both regions show a similar behavior on a monthly basis. From March to August, the FOREST simulations show similar monthly values compared to the EVAL simulations. In contrast, the GRASS simulations show generally lower monthly precipitation values during the spring and summer months. This is observed over both

regions, with GRASS showing 10 to 20 mm less than the EVAL and FOREST runs. During the dryer months, the three simulations share generally similar values. The temperature panels, both maximum and minimum values, show similar behavior. The winter and spring months display lower temperatures with the GRASS simulations, particularly for the minimum temperatures during the winter months.

Compared to other RCMs in the LUCAS project, CRCM5 shows greater sensitivity to forestation, though a consistent winter–spring warming is observed across all models (Asselin 2022). In the FOREST simulation, this warming is mainly due to reduced surface albedo from snow-masking by evergreen needleleaf forests (Asselin et al., 2022; Davin et al., 2020; Duveiller et al., 2018; Li 2015). Strong short-wave radiation fluxes at the lower latitude of northern needleleaf forests in North America further amplify this winter and spring warming (Asselin 2022). As shown in Fig. 5, the warming relative to EVAL is modest because EVAL already contains a high fraction of needleleaf forest (Fig. 2). In contrast, the GRASS simulation cools winter and spring temperatures due to the higher surface albedo from snow cover. During summer, FOREST enhances evapotranspiration, particularly over broadleaf forests, which increases precipitation relative to GRASS (Fig. 5). We found that bias correction made only minor adjustments to the RCM outputs. For instance, the mean annual precipitation and temperature patterns remained essentially the same before and after correction. Thus, the differences observed between FOREST and GRASS precipitation in GRASS during spring–summer, or cooler winter temperatures in GRASS are genuine outcomes of the land-use differences rather than artifacts of bias correction

4.3. Hydrological response to land use scenarios

In this stage, the streamflow simulations obtained with the HYDROTEL model coupled with three CRCM5 simulations are compared with the four selected flood indices, as well as the mean annual hydrographs.

4.3.1. Impacts on flood indices

To evaluate the impacts of the land-use changes on flood events, Fig. 6 to9 show the four flood indices estimated from the three CRCM5-CLASS and grouped in three catchment size classes, less than 100 km^2 (S for small), 100–1,000 km^2 (M for medium), and above 1,000 km^2 (L for
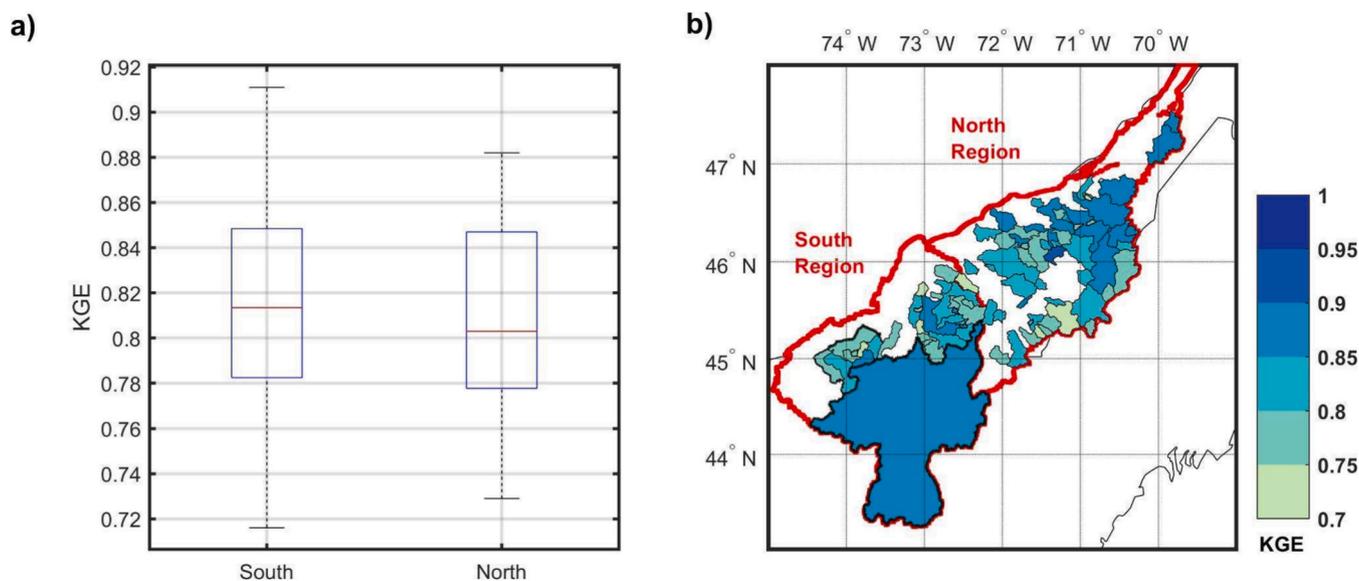

Fig. 4. KGE values estimated over the full time series of the studied catchments. The two greater regions, the north and south regions, are highlighted in red. The north and south regions contain 56 and 33 catchments, respectively. The two catchments selected for further analysis are highlighted with bold outlines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
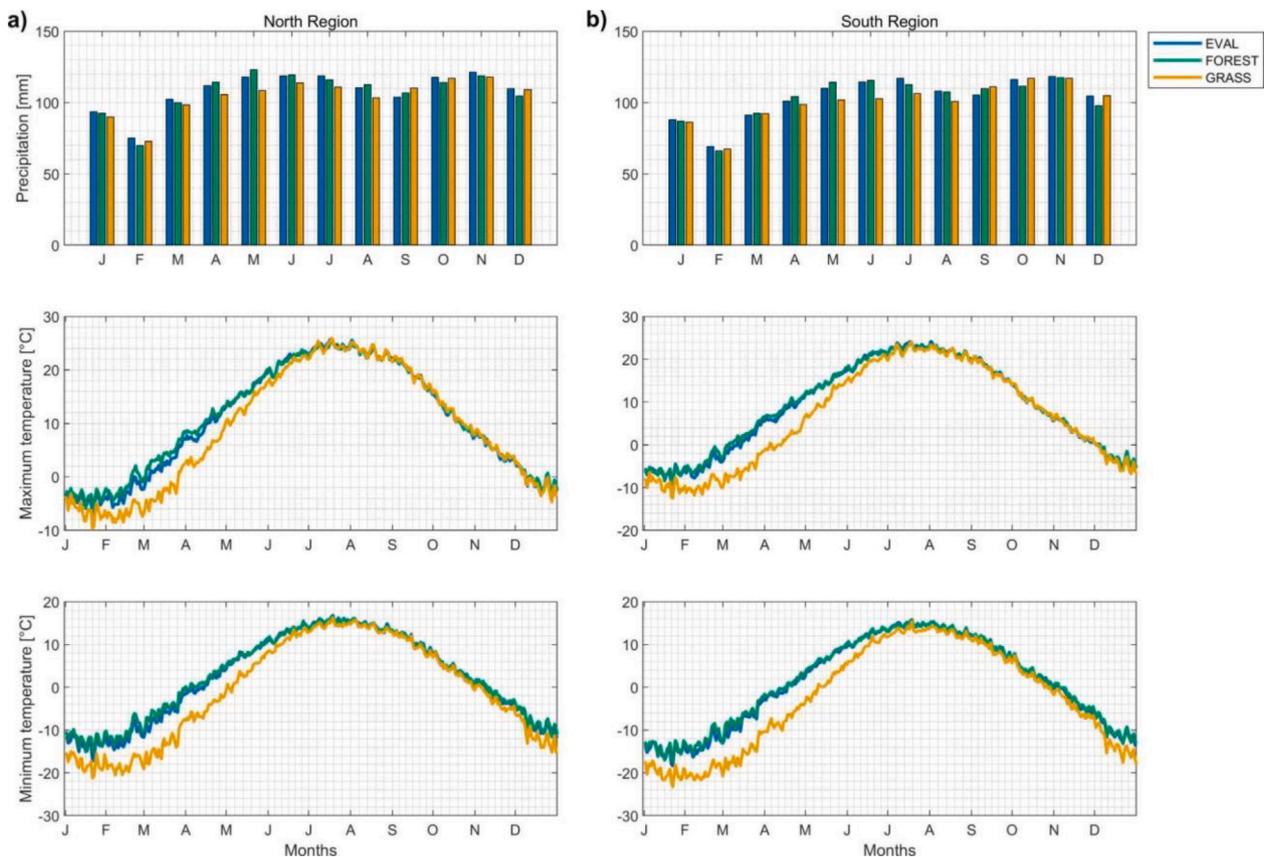
Fig. 5. Mean annual precipitation, maximum and minimum temperatures of the three CRCM5 simulations. a) North region. b) South region.

large).

The first index presented in Fig. 6 panel "a", *Q1MAXAN*, shows the behavior of the annual maximum streamflows for the 2- and 100-year return periods, normalized by the mean annual streamflow of each catchment. Results obtained with the other return-periods (5-, 10-, 20-, and 350-year return periods) were generally similar to the 100-year return period results. Thus, only the 2- and 100-year return periods will be presented. Overall, the results show that the GRASS simulations produced higher mean annual peak events over both return periods. This effect is especially observed in the smaller catchments, and it gradually diminishes with increasing catchment sizes. Similarly, the normalized mean winter-spring peaks (i.e, *Q1MAXWS*) presented in Fig. 6 "b" show generally larger peak values with the GRASS simulation when compared against the reference simulation (i.e., EVAL). This similarity was expected as the maximum annual peaks of the studied catchments are generally observed during the spring melt.

Fig. 6 "c" shows the impact of the different land uses over the mean summer-fall peaks for the different return periods and catchment sizes. No clear behavior is observed over the different return periods. Yet, the *Q1MAXSF* values estimated for the 2-year return period shows slightly larger peak values with the FOREST simulation. Yet, for the 100-year return period, the GRASS simulations show higher summer-fall peak values when comparing it against the EVAL simulation. This effect can be linked to the observed higher precipitation in the FOREST simulations observed in Fig. 5. Additionally, the higher number of precipitation events might have a higher impact in the smallest basins, as smaller regions can be fully covered by a single precipitation event.

Fig. 6 "d" displays the impact of land use change on the day of occurrence of the winter-spring peaks. The boxplots show that, in line with the general behavior of the indices in panels "a"-"c", the GRASS simulations also showed a larger impact on the timing of the winter-spring peaks. In other words, it is observed that severe land use

changes to grass result in a delayed and very likely increased winter-spring peak.

Finally, regarding the impact of catchment size on flood indices, our results indicate that smaller catchments were generally more sensitive to land-use changes, particularly under the GRASS scenario, which produced higher and delayed peaks. This is confirmed by the Kruskal–Wallis statistical tests (Kruskal & Wallis, 1952) presented in Figure SIII of Supplementary Material III, which show that the Q1MAXAN and Q1MAXWS indices from the GRASS simulations in the small-catchment group are statistically different from all corresponding EVAL and FOREST boxplots. This greater sensitivity can be explained by the dominant flood-generation processes: in small basins, infiltration-excess runoff is the prevailing mechanism, and this process responds strongly to land-surface characteristics such as vegetation cover, root depth, and soil compaction. Removal of canopy cover in GRASS increases snow accumulation and reduces interception, which, when coupled with reduced evapotranspiration, enhances infiltration-excess runoff and magnifies flood responses. In contrast, larger catchments tend to be dominated by saturation-excess runoff processes, which depend more on antecedent wetness, topographic convergence, and floodplain storage than on immediate land-surface changes. These processes buffer the impact of extreme land-use alterations, leading to a smaller relative difference between FOREST, GRASS, and EVAL simulations. Additionally, larger catchments integrate a greater diversity of physiographic conditions and sub-basin responses, which smooths out localized extremes seen in smaller systems.

It is important to note that the absence of a clear monotonic relationship between catchment size and flood-index change reflects this process heterogeneity rather than model inconsistency. For example, some medium-sized catchments with high snow fraction or limited storage capacity may exhibit responses similar to small basins, while others with extensive wetlands or floodplains behave more like large
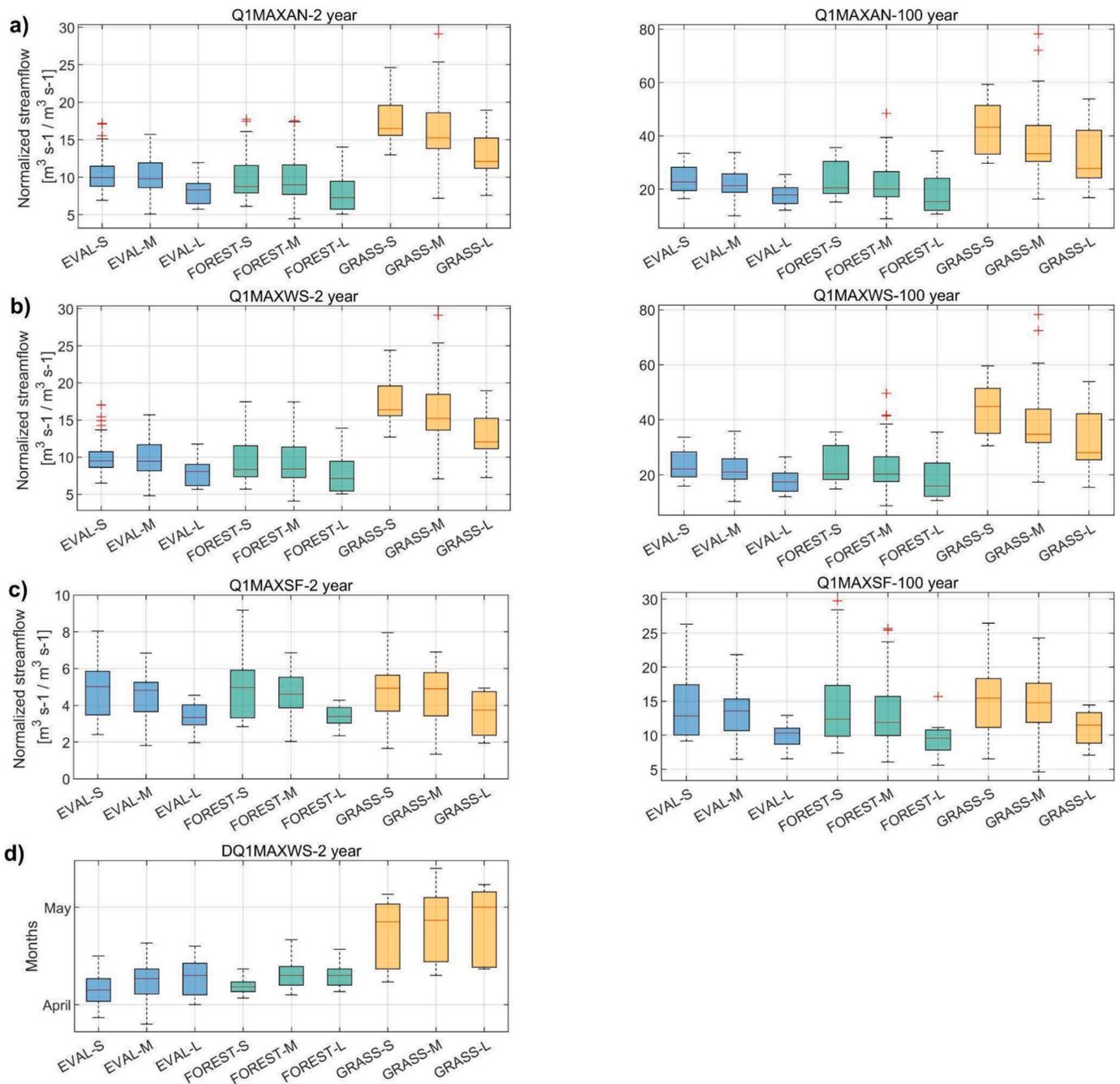
Fig. 6. Flood indices estimated for the EVAL, GRASS, and FOREST CRCM5-CLASS simulations for the small (−S), medium (−M), and large (−L) catchment groups. The normalized 2- and 100-year return periods for the annual maximum daily streamflow (Q1MAXAN; panel a), winter-spring maximum daily streamflow (Q1MAXWS; panel b), summer-fall maximum daily streamflow (Q1MAXSF; panel c), and the average day of occurrence of the maximum daily winter-spring streamflow (DQ1MAXWS; panel d) are shown.

basins. Therefore, while catchment size influences the degree of hydrological sensitivity, the dominant runoff process (infiltration- vs. saturation-excess) and local physiographic controls are the primary drivers of the observed variability.

4.3.2. Mean annual hydrographs

Fig. 7 illustrates the mean annual values of the hydrological variables in a daily time-step simulation for Richelieu (left column) and Châteauguay (right column) catchments. The simulation, which uses ERA5 as a reference for comparison, serves as the benchmark. The EVAL simulation closely follows the ERA5 simulations in terms of both timing and magnitude of the peak values for (panel a and b). The Eval

simulation closely follows the ERA5 simulations in terms of both timing and magnitude of the peak values for the Richelieu catchment (panel a). This similarity extends throughout the rest of the year. Considering that the climate model is based on ERA-Interim and the land-use in the Eval simulation resembles the current conditions on which the ERA5 simulation was implemented, the similarities between these two cases were expected.

The GRASS simulation exhibits deviations in reproducing the timing and magnitude of the peak compared to the ERA5 simulation. There is a significant overestimation of the peak, coupled with a substantial delay in time of the peak. Additionally, the winter streamflow is considerably underestimated when compared to other simulations. This is because the
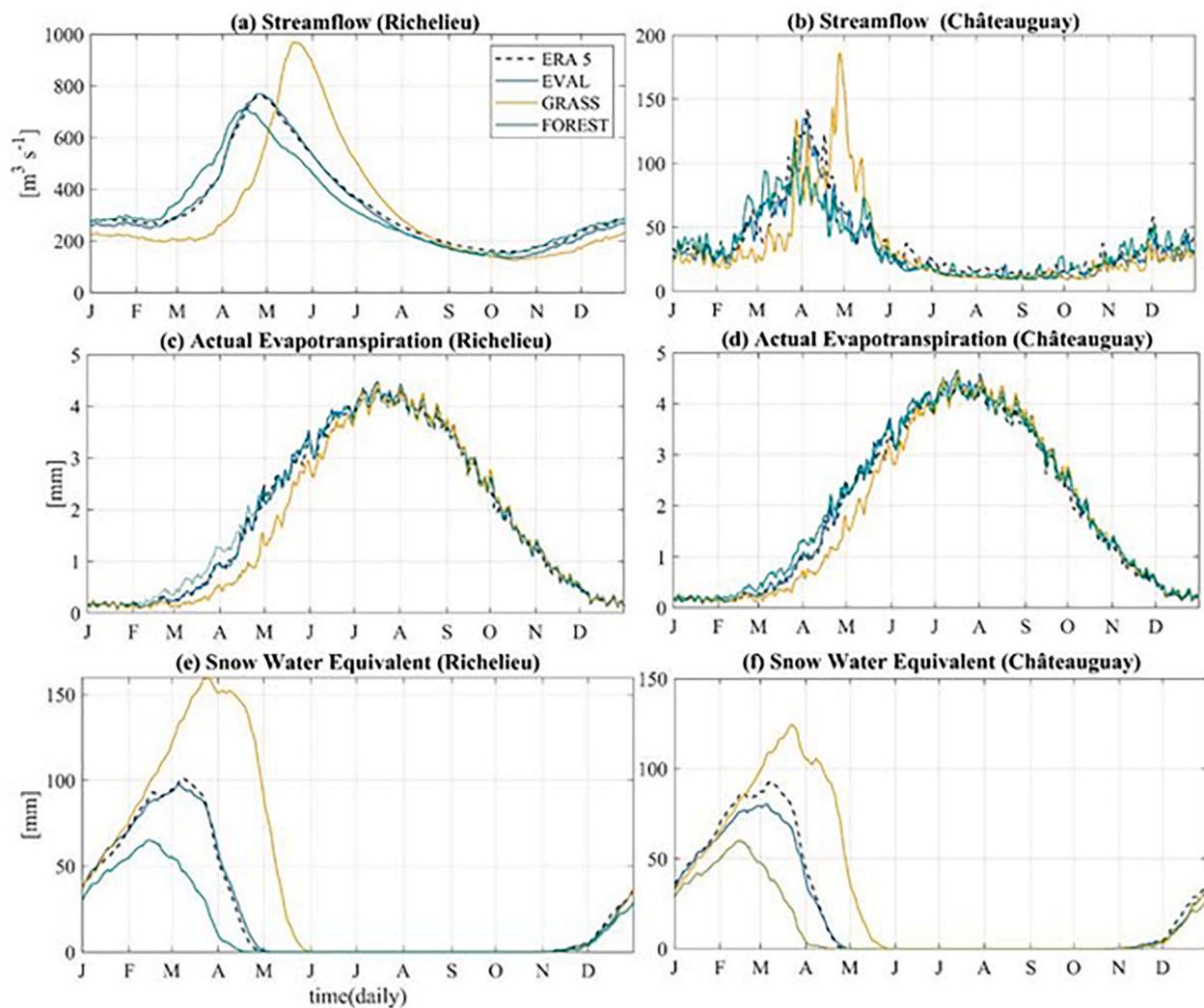
Fig. 7. Mean annual variation of hydrological variables for Richelieu (left) and Chateauguay (right): a and b) Streamflow, c and d) Actual Evapotranspiration (AET), e and f) Snow Water Equivalent (SWE).

simulated temperature of the grass dataset is lower than that of other climate simulations, leading to a significant snow accumulation during the winter months (panels e and f). Given the near-freezing temperatures, the effects of lower AET (panels c and d) during the winter months are negligible on streamflow production. The simulated streamflow returns to its normal pattern after July, resembling the other simulations following a delayed melting period, which extends to the month of August for the Richelieu catchment.

The FOREST simulation displays behavior quite contrary to that of the GRASS simulation. The peak of the hydrograph is significantly lower than that of EVAL simulations, with the peak occurring earlier than in the Eval simulations. The winter flow is substantially higher compared to the other hydrographs. This can be attributed to the higher temperature from the climate model. Panels (e and f) indicate significantly lower snow accumulation during the winter months for the Forest simulation compared to ERA5. Additionally, the timing of the peak in mid-February is much earlier than typically expected for the region.

4.3.3. Swapped simulations

Fig. 8 compares and contrasts the results of swapped simulations with other simulations, using two distributed models, WaSiM and HYDROTEL.

In Fig. 8, panels (a) and (b), the hydrograph of the Swapped FOREST simulation exhibits similarities with the GRASS simulation. Both

simulations feature a significantly larger peak later in the year compared to the ERA5 simulation, along with substantially lower winter flow than the ERA5 simulation. HYDROTEL demonstrates an even greater lag in the timing of the peak relative to its GRASS simulation, whereas WaSiM's Swapped FOREST closely mirrors the GRASS simulation in both the timing and magnitude of the peak. The contrasting behaviors observed in the WaSiM and HYDROTEL simulations can be attributed to differences in their snow models, as shown in panels (c) and (d). WaSiM's snow accumulation for the Swapped FOREST and GRASS simulations appears identical, while HYDROTEL exhibits nearly 50 % higher snow accumulation and a delayed snowmelt compared to the GRASS simulation. This is consistent with WaSiM's more physically-based but generic snow model, which apparently does not differentiate between forest and open areas (as noted in our methodology description). (see Section 5 for further discussion).

Similarly, the Swapped GRASS simulation exhibits behavior similar to the FOREST simulation. In WaSiM, as shown in panel (a), the Swapped GRASS simulation closely follows the FOREST simulation, though its magnitude is slightly higher. This difference arises from the lower AET observed in the Swapped GRASS simulation compared to the FOREST simulation, as illustrated in panel (e). For HYDROTEL, the Swapped GRASS simulation shows a smaller peak magnitude than the FOREST simulation, with the peak occurring earlier. Additionally, the winter flow in the Swapped GRASS simulation is higher than that of the
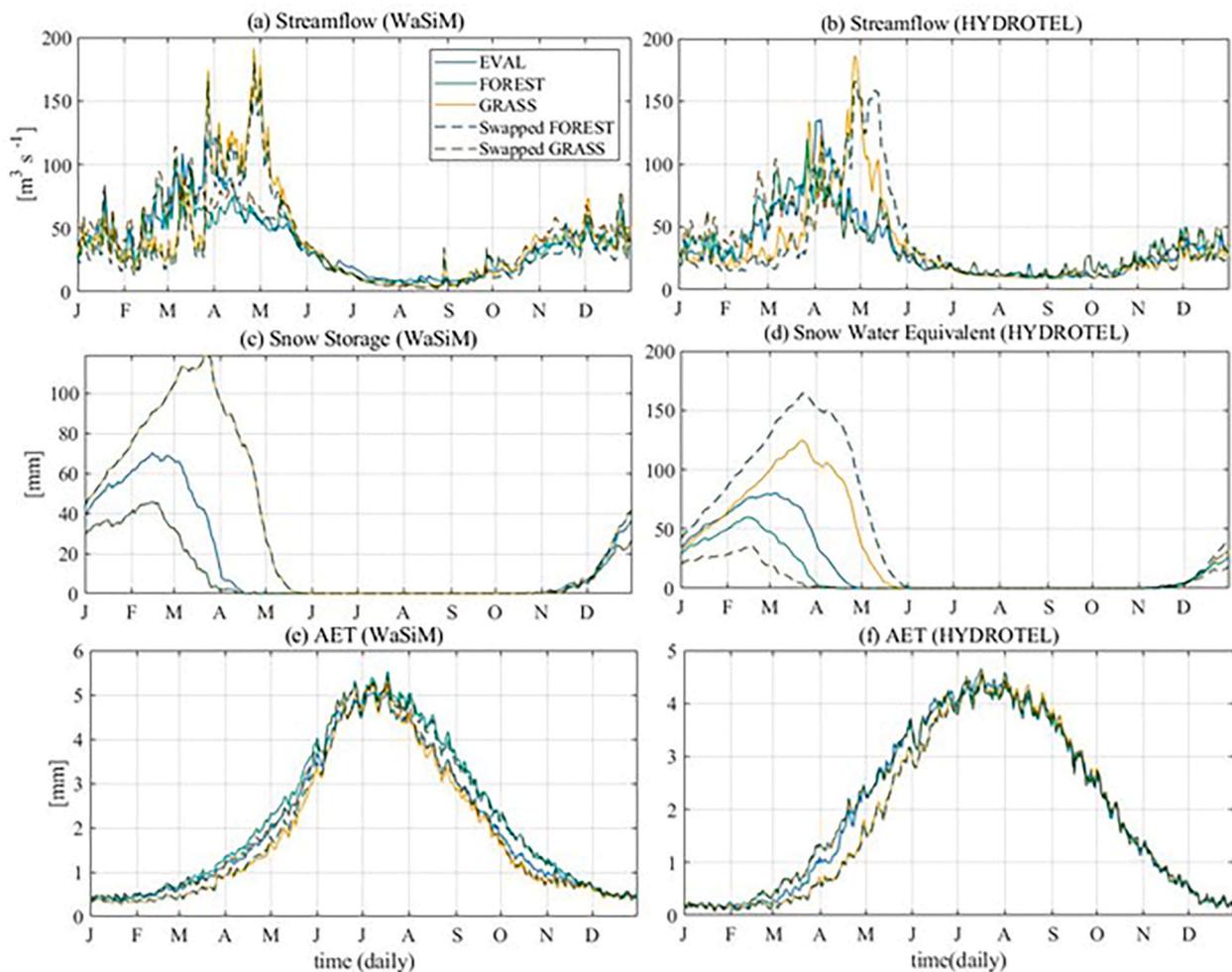
Fig. 8. Comparing mean annual variation of hydrological variables for the Châteauguay catchment using WaSiM and HYDROTEL: a and b) streamflow, c and d) snow storage (WaSiM) and snow water equivalent (HYDROTEL), e and f) actual evapotranspiration.

FOREST simulation. These differences can be attributed to lower snow accumulation in the Swapped GRASS simulation, as depicted in panel (d), compared to the FOREST simulation (see Section 5 for further discussion).

5. Discussion

1. Land-use changes and the spatio-temporal distribution of land use are generally believed to significantly affect hydrological responses in small-scale catchments (Hurtado-Pidal et al., 2022; McGrane, 2016; Wang et al., 2023). However, less sensitivity has been observed at the regional scale (Chen et al., 2021), which is mainly attributed to differences in scale and the relative magnitude of projected changes compared to the catchment area. Additionally, the combined impact of land-use and climate change is often dominated by the climate driver, particularly in larger catchments. In this context, most studies focused on the impact of GHG-driven climate drivers and its comparison with the land use change impact while less attention has been paid to the biophysical effects of land use change on climate. The latter can potentially modify hydrological responses (Asselin et al., 2022; Khadka et al., 2024). Our study demonstrates that in extreme cases of land-use change, such as afforestation or reforestation, this feedback mechanism significantly alters climate signals and therefore runoff production including peak flows, and the timing of the peaks (Figs. 6–12).
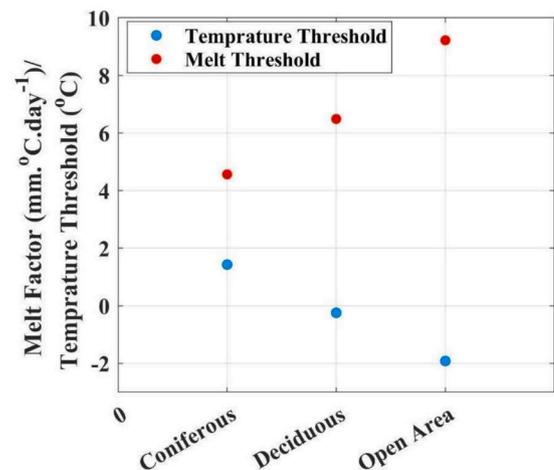

Fig. 9. HYDROTEL temperature threshold and melt threshold parameters calibrated for the Monteregie Region, Quebec.

2. The SWAT model has been widely used to assess the impact of land-use changes (e.g., Ghaffari et al., 2010; Liu et al., 2024; Chen et al., 2021; Dolgorsuren et al., 2024), exemplifying legacy selection in hydrological modeling (Addor and Melsen, 2019). The potential contributions of hydrological models in land-use impact studies have
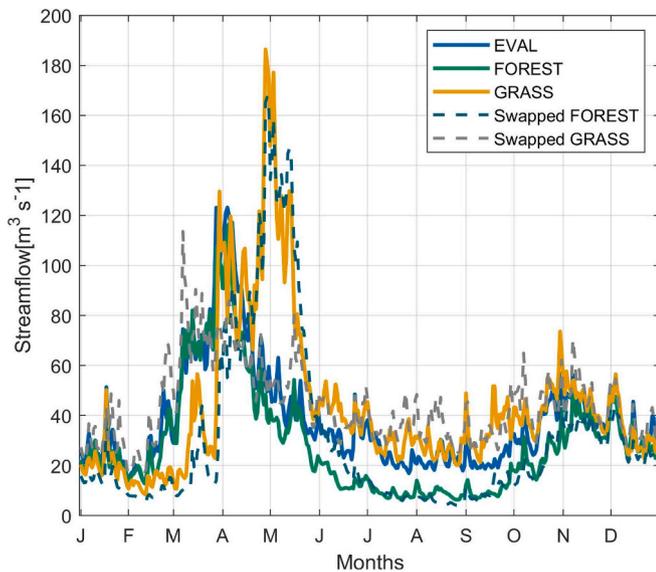
Fig. 10. Comparing mean annual hydrographs for the Châteauguay catchment using GR7J model.

been poorly understood. Variations in the representation of hydrological processes across models, in terms of methodology and complexity, can lead to significant differences in simulation outputs. Furthermore, many distributed hydrological models are developed with the specific hydrological conditions of particular regions in mind, which can result in inaccuracies when applied to different hydro-climatic zones. In the following, we aim to characterize the role of the hydrological models used in this study to simulate land-use change impacts.

a. Regarding WaSiM, unlike HYDROTEL (Fig. 8, right column), the GRASS-Swapped FOREST and FOREST-Swapped GRASS differences, in terms of snow cover (panel c in Fig. 14) are identical. This is because, WaSiM does not account for the impact of land use in its snow module, therefore only the feedback effect of land use change on climate is "seen" by the model and simulated. HYDROTEL employs a mixed degree-day equation (Eq. (1)) for snow accumulation and melt, with two parameters calibrated for each land use class: T_s (temperature threshold for snowmelt) and C_f (melt factor,)

$$M_s(s) = C_f(c)\frac{R_p}{R_h}(T_a - T_s)(1 - a) + 0.0125PT_a \quad (1)$$

The equation defines M_s as the rate of snowmelt at the interface between snow and air (mm.day^{-1}). Here, C_f represents the melt factor specific to land use class (mm.°C.day^{-1}), and c denotes the index for land use classification (coniferous forests, deciduous forests and open areas in the present case). The variables R_p and R_h are radiation indices corresponding to sloped and flat surfaces, respectively (Frank and Lee, 1966). T_a indicates mean daily air temperature (°C), while T_s is the threshold temperature for initiating melting (°C). Additionally, a refers to snow albedo, and P represents rainfall (mm).

Fig. 9 illustrates the values of these parameters for the South region (Fig. 4), which include both Richelieu and Châteauguay catchments. When the land cover changes from open areas to forest, T_s increases and C_f decreases, leading to reduced snow melt and increased snow accumulation (Eq. (1)). Therefore, it is anticipated that transitioning from GRASS to FOREST would reduce the melt factor, thereby leading to increased snow accumulation. However, this expectation is contradicted by the results, as the GRASS simulation exhibits higher snow accumulation than the FOREST simulation when compared to the EVAL simulation (Figs. 7 and 8). This unexpected behavior can be attributed to the climate forcing itself: the simulated temperature for GRASS is lower, and

for FOREST, higher, compared to the EVAL simulation (Fig. 5). These temperature differences offset the impact of land-use change, driving the catchments' behavior in an opposing direction. Consequently, the Swapped simulations demonstrate even greater deviations, with GRASS showing increased snow accumulation and FOREST showing decreased snow accumulation. This outcome arises because both driving factors—extreme land-use change change and its associated climate feedback—act in the same direction, producing a resonance-like response in the HYDROTEL model.

b. Fig. 8 panels e) and f) highlight key differences in evapotranspiration between the two models. In WaSiM, the FOREST simulation shows higher evapotranspiration from July to November, which lowers streamflow relative to EVAL. This occurs because WaSiM explicitly links soil water content and transpiration (Schulla & Jasper, 2007), so full forest cover increases transpiration and latent heat flux, consistent with the cooling effect of broadleaf forests reported by Asselin et al. (2022). In contrast, HYDROTEL simulates higher streamflow in FOREST than in EVAL during the same period. Although HYDROTEL can differentiate evapotranspiration by land cover, its AET is largely governed by high soil water content in the study region, minimizing land-use impacts. As a result, HYDROTEL's GRASS and swapped FOREST simulations yield similar AET, and likewise for FOREST and swapped GRASS.

c. The observed variations in sensitivity between hydrological models underscore the critical role of model selection. To further illustrate this, the mean annual hydrograph analysis presented in Fig. 8 was also conducted using a lumped hydrological model that incorporates sensitivity to land use changes. This model is a modified version of the lumped GR4J hydrological model (Perrin et al., 2003), coupled with the CemaNeige snow model (Valéry et al., 2014) and the Oudin potential evapotranspiration (PET) formulation (Oudin et al., 2005). The modified GR4J-CemaNeige-Oudin model integrates two primary land cover types (i.e., forested and open areas) by adjusting the parameters of the snow and PET models. These modifications resulted in a total of seven parameters, leading to the model being referred to as GR7J. Further details on this lumped model are provided in Supplementary Material I.

The GR7J simulations for the EVAL, FOREST, GRASS, and swapped scenarios are presented in Fig. 10. These hydrographs indicate that GR7J is sensitive not only during the spring melt but also in summer, where streamflow in the FOREST simulation is consistently about 50 % lower compared to the EVAL and GRASS simulations. This year-round sensitivity was expected, as both the PET and snow modules of GR7J are influenced by land use changes. This finding is further supported by the swapped simulation analysis, which—unlike the results obtained with WaSIM and HYDROTEL (see Fig. 8)—reveals clear differences against the FOREST and GRASS simulations. The contrasting results produced by a lumped model such as GR7J are not intended to determine which model best represents land use changes but rather to emphasize the potential influence of hydrological model structures on land use change representations.

3. Notwithstanding the differences in the sensitivities of the hydrological models to land use, the biophysical effects of LUC in terms of feedback on climate appears to be the major driver of the hydrological response during the spring freshet. This aligns, at least for that season of the year, with the findings from the literature, as discussed earlier. That being said, more work remains to be done to (1) keep improving and validating the hydrological models formulations in terms of their sensitivity to land use changes; and (2) deepen our understanding of the impacts of land use changes versus the biophysical effects of LUC on catchment hydrology. Three hydrological models were compared in the present study therefore other models should be involved in further investigations.

4. Uncertainty in this study's findings arises first from the climate forcing data. The regional climate model (CRCM5) simulations, even after bias correction with ERA5, have inherent resolution and bias limitations. At ~ 12 km grid spacing, they may not capture fine-scale snow accumulation and melt processes in complex terrain; forcing a hydrological model with coarser meteorological inputs can introduce spatially heterogeneous errors in runoff timing and magnitude (Maina et al, 2020). Moreover, reanalysis and model biases in winter conditions propagate into the results. For example, ERA5 is known to substantially overestimate snow water equivalent (by roughly 150–200 % on a broad scale) relative to observations (Kouki et al, 2023). Evaluations of CRCM5 similarly indicate biases, a generally near-zero mean cold-season temperature bias over southern Québec but a slight wet bias in winter precipitation (e.g., excess snowfall in western Québec, McCray et al.,2023), which could skew simulated snowmelt volumes. These biases in climate inputs translate into uncertainty in simulated spring flood peaks. Additionally, the treatment of land–atmosphere feedbacks in the climate forcing is a major uncertainty. While our idealized FOREST and GRASS scenarios were run through the RCM to account for feedback, the strength and realism of those feedbacks depend on model physics. Large-scale deforestation, for instance, can reduce regional evapotranspiration and even precipitation, leading to increased runoff (Douville et al, 2021), but climate models vary in how strongly they reproduce such effects. If the RCM under- or overestimates land-use-climate interactions (for example, changes in snow albedo or canopy sublimation), it could lead to an overconfident or understated signal in spring flood response. In summary, uncertainties in climate forcing resolution and biases, especially related to snow processes and land–atmosphere coupling, limit the precision of our flood projections under land-use change.

5. The FOREST vs. GRASS end-members likely bracket the extreme responses, but actual land-use changes happen as mosaics and gradually, real-world responses may be more muted. Furthermore, land-use impacts on floods are highly context-dependent. Catchment characteristics (size, storage capacity, initial conditions) and event scales determine whether land cover exerts a strong control on peak flows (Sharifinejad and Hassanzadeh, 2023). For instance, forest cover can delay snowmelt and attenuate small to moderate runoff events, but it offers minimal protection against extreme flood events in some settings. Likewise, the direction and magnitude of land-use effects can vary with climate: a change that reduces floods in a snow-dominated, energy-limited system might have a different outcome in a rain-fed or arid catchment. Therefore, caution is warranted in extrapolating our southern Québec findings to other regions or climate regimes. Our results highlight processes of forest-snow interaction and land-climate feedback that are likely relevant beyond our study area, but the quantitative outcomes (e.g., a "delayed, larger" spring peak under grassland) could differ elsewhere. Overall, acknowledging these uncertainties, in climate forcing, model structure, and case-specific factors is crucial. They suggest the need for ensemble approaches (multiple climate models, multiple hydrological models, and scenarios) to robustly assess spring flood sensitivity to land-use change, and they temper the conclusions by recognizing that our modeled outcomes are one realization within a broader range of plausible futures.

6. Conclusions

In this study, a semi-distributed hydrological model and three RCM simulations with contrasting land uses were combined to evaluate the impacts of severe land use changes on flooding simulations. The hydrological simulations of eighty-nine basins located in the south of the Canadian province of Quebec were evaluated using four flood indices and mean hydroclimatic conditions. A fully distributed model and a land-use sensitive lumped model were involved in additional analyses.

Overall, the results suggest that the severe land use change can impact the timing and magnitude of floods. The different evaluations performed in this study led to the following key findings:

1. Afforestation, i.e. changes from FOREST to GRASS land use, resulted in higher and delayed winter-spring flood peaks on the studied catchments.
2. Snowmelt-driven peak flows showed a larger impact from severe land use changes due to their combined effects of precipitation and temperature changes.
3. The level of hydrological sensitivity to land use is impacted by the hydrological model's structure. In other words, the internal formulations (e.g. evapotranspiration, snow modeling) of a given hydrological model can lead to different hydrological responses.
4. The feedback effects of land use change on climate (i.e., precipitation and temperature) are a more important driver than the direct effects of land use change on hydrological model processes (i.e., evapotranspiration, snow accumulation, and snowmelt) in simulating the spring floods in two of the studied catchments, and this should be further investigated.

The analyses and discussions provided in this study brought in valuable insights on the potential effects of land use changes on flood simulations. This finding implies that land-use planning for flood mitigation should account not only for direct hydrological changes but also for the indirect effects via climate. In other words, large-scale afforestation or deforestation can alter regional climate in ways that substantially affect flood risk, which water resource managers and policymakers need to consider. The results indicate that forest management and vegetation change can substantially modify snow accumulation, melt timing, and spring flood responses through land–atmosphere feedbacks. Therefore, accounting for dynamic land-surface processes is important for robust flood-risk assessment and climate-adaptation planning in snow-dominated regions. However, the inherent methodological limitations of the analyses pave the way for further investigations. For instance, it can be recommended that future efforts focus on quantifying the uncertainty related to hydrological models and their internal formulations. Additionally, integrating more diverse catchments can lead to a better understanding of the link between hydroclimatic streamflow-generating processes (e.g., snowmelt, precipitation events) and land use changes. Furthermore, future work should examine intermediate land-use change scenarios (to see if effects scale linearly or nonlinearly between our extreme cases) and incorporate additional climate models to capture uncertainty in climate–land feedback responses. Moreover, assessing statistical significance of flood changes and including more catchments with differing snow regimes would help generalize these results.

CRediT authorship contribution statement

Siavash Pouryousefi Markhali: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis. **Mariana Castañeda Gonzalez:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis. **Béatrice Turcotte:** Formal analysis. **Annie Poulin:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Formal analysis. **Jean-Luc Martel:** Writing – review & editing. **Richard Arsenault:** Writing – review & editing, Conceptualization. **François Brissette:** Writing – review & editing, Conceptualization. **Olivier Asselin:** Writing – review & editing, Conceptualization. **Richard Turcotte:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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Data availability

Data will be made available on request.

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