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Impacts of climate change on streamflow in the McKenzie Creek watershed in the Great Lakes region

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Introduction: This study explored streamflow dynamics of the McKenzie Creek watershed in Southern Ontario, Canada under a changing climate. The Creek is located in the southern portion of the Grand River watershed in the Great Lakes region and is an important water and ecosystem service provider for the Six Nations of the Grand River reserve, the largest (by population) Indigenous community in Canada and the fourth largest in North America.

Methods: The Coupled Groundwater and Surface-Water Flow Model (GSFLOW) was used to simulate streamflow from 1951 to 2020 using observed gridded meteorological data from Natural Resources Canada (NRCANmet) and *in situ* data from Environment and Climate Change Canada (ECCC). Downscaled data from the Coupled Model Intercomparison Project Phase 5 (CMIP5) for two Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathways (RCP) climate warming scenarios, RCP 4.5 and RCP 8.5 were used to run GSFLOW for the historic (1951–2020) and projected (2021–2099) period.

Results: Results suggested that streamflow in the McKenzie Creek will be significantly impacted by climate change in winter months when streamflow is projected to increase due to higher temperatures causing early melting of snowpack and increasing winter precipitation. Consequently, spring streamflow is expected to decrease and little or no change in streamflow in the summer and autumn. These changes in streamflow dynamics may lead to more flooding incidents in the winter, while at the same time, the region may face reduced water availability or dry conditions in late spring and summer due to warm temperatures.

Discussion: This study provides important information about streamflow and hydrologic dynamics of this watershed that will help managers and planners to better manage water resources and be prepared to deal with climate change and its impacts on water availability and security not only for the Six Nations area but also for Southern Ontario which houses one-third of Canada's population.

KEYWORDS

climate change, climate change impacts, hydrology, streamflow, GSFLOW integrated hydrologic model, Six Nations of the Grand River, Indigenous

1 Introduction

Climate change projections for the eastern Great Lakes region in North America indicate that annual average temperature will increase between 2.3°C and 7.9°C and total precipitation will increase by 72–123 mm by the end of the 21st century (IPCC, 2013; McDermid et al., 2015a; Bush and Lemmen, 2019). Consequently, the frequency and duration of extreme warm temperatures and the frequency and intensity of extreme precipitation events are expected to increase (d'Orgeville et al., 2014; Deng et al., 2016; Razavi et al., 2016; Wazneh et al., 2017; Zhang et al., 2020; Deen et al., 2021). These changes in temperature and precipitation dynamics have the potential for impacting environmental, ecological, and hydrological dynamics in the region, especially streamflow (Dudley et al., 2017; Wuebbles et al., 2019; Douville et al., 2021; Wang et al., 2021). For communities located near rivers and streams, especially rural and Indigenous communities, these changes in streamflow may entail serious consequences, such as flooding, summer water stress, lower ecosystem productivity and other infrastructure, social, and economic impacts. Given the continued rise in atmospheric greenhouse gasses (GHGs), it is very important to access the potential impacts of future climate change on streamflow and watersheds in the Great Lakes region, which houses more than 30% and roughly 10% of the populations of Canada and the United States, respectively (Gulev et al., 2021; EPA, 2023). Such studies and analyses are essential for developing strategies for climate change adaptation, disaster risk reduction, and water resource planning ranging from the community to watershed to regional scale and decision-support frameworks (Morand et al., 2015; IPCC, 2022).

In the literature many hydrologic studies have been published exploring climate change impacts on watershed hydrology and streamflow in the Great Lakes region (Cherkauer and Sinha, 2010; Crossman et al., 2013; McDermid et al., 2015b; Erler et al., 2019; Costa et al., 2021; Mai et al., 2022). However, recent streamflow studies have been conducted in medium to large size watersheds, such as the Thames and Grand River watersheds which are among the largest watersheds in Southern Ontario, Canada (Champagne et al., 2019; Champagne et al., 2020a; Champagne et al., 2020b; Hanief and Laursen, 2017; Kaur et al., 2019; Li et al., 2016; Liu et al., 2016; Philip et al., 2022; Rahman et al., 2012; Zhang et al., 2018) and Western New York watersheds in the United States (Soonthornrangsan and Lowry, 2021). In the literature, with some exceptions (e.g., Grillakis et al., 2011; Ahmet and Tsanis, 2016; Buttle, 2018; Larocque et al., 2019; Persaud et al., 2020), there is a lack of studies focusing on streamflow of smaller streams or tributaries in this region and exploring how the streamflow of smaller streams or tributaries may be impacted by climate change and extreme weather events. Streamflow of these smaller streams or tributaries is much more vulnerable to climate change and extreme weather impacts due to the smaller size of their catchments and command areas and challenges due to the timing of future water availability in relation to higher demand in the growing season (Larocque et al., 2019). Often entire communities depend on these smaller streams or tributaries for their water and ecosystem services. These communities will be much more vulnerable to future water stress or flooding events. One such example is the Six Nations of Grand River reserve (Six Nations), which is the largest Indigenous community in Canada with approximately 13,000 people living in the reserve (GWF, 2022). It is also the fourth largest reserve in North America (Norris et al., 2012). This Indigenous community relies heavily on the McKenzie Creek, which is a small tributary of the Grand River for its water and ecosystem services (MacVeigh et al., 2016). This reliance has increased the vulnerability of the community to climatic stresses and undermines the security of future water resources. Although a number of water related issues have been highlighted for the Six Nations community including, but not limited to water quality (Makhdom, 2021), access to water (Chattopadhyay, 2018), water governance (Martin-Hill et al., 2022) and community health (Duignan et al., 2020; Duignan et al., 2022; Sultana et al., 2022), no comprehensive study has been conducted exploring the impacts of future climate change and extreme events on streamflow and water balance of the McKenzie Creek. Such studies and analyses for different future climate change scenarios are critical for developing water related planning and decision-support frameworks for the community.

As a part of the Global Water Futures Program's (GWF) Co-Creation of Indigenous Water Quality Tools (Co-Creation) initiative, which strives to better understand water related issues within the Six Nations of the Grand River, this study was conducted to determine the impacts of climate change on the McKenzie Creek watershed. The specific objectives of our study are to i) analyze the past trends and conduct future simulations of streamflow of the McKenzie Creek of the Grand River in Southern Ontario, Canada under two IPCC climate warming scenarios, Representative Concentration Pathways (RCP) 4.5 and 8.5 and ii) determine how climate change may impact the dynamics of streamflow in the McKenzie Creek. Indigenous groups are recognized to face exacerbated levels of vulnerability to climate change (IPCC, 2022), and within Canada, Indigenous focused data and information is "woefully insufficient" (Indigenous Services Canada, 2022). This study will help to provide valuable information required to ensure the security of water resources for Six Nations of Grand River and prepare the community and others in Southern Ontario and the eastern Great Lakes region to deal with climate change impacts.

2 Materials and methods

2.1 Study area

The McKenzie Creek watershed is a tributary of the southern portion of the Grand River watershed, which is the largest watershed in Southern Ontario (Figure 1). The watershed covers an area of 194 km^2 and borders Brant County, Six Nations of the Grand River reserve, and Haldimand County. It provides these communities with water and other ecosystem services for activities such as dewatering (45%), agriculture (30%), industry (21%), and commerce (4%) (Wong, 2011). The Creek has a mean annual flow of 1.9 $m^3 s^{-1}$ or 350 mm $year^{-1}$ and joins with the Boston Creek before discharging into the Grand River near the York flow station of the Grand River Conservation Authority (MacVeigh et al., 2016).

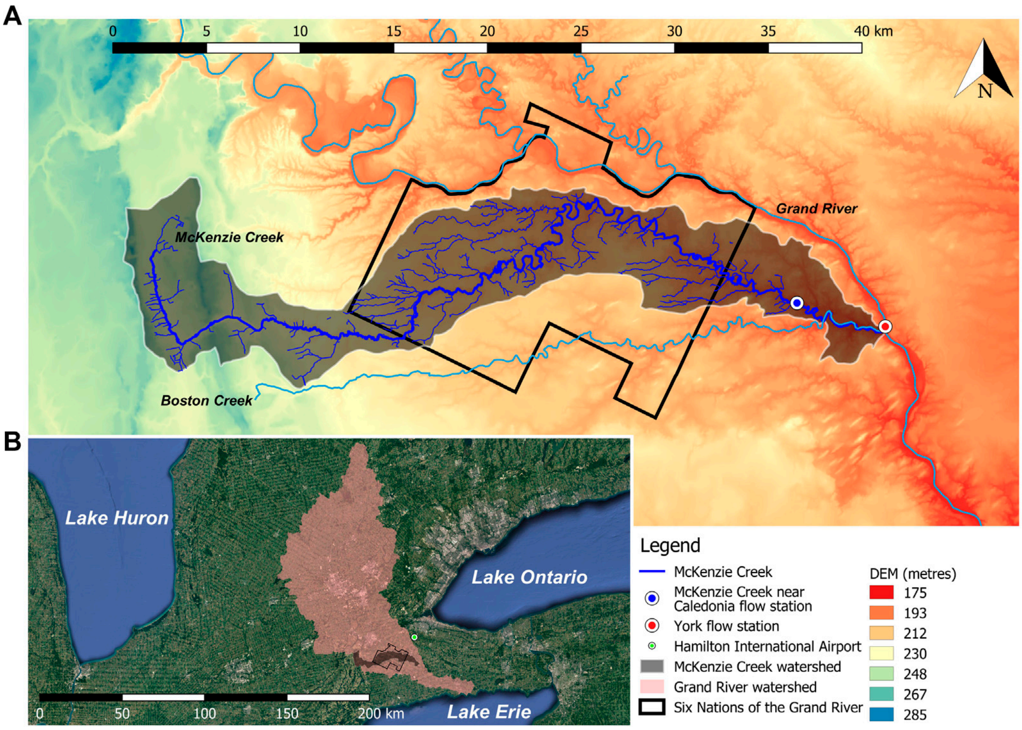

FIGURE 1
Map of the study area. **(A)** Digital Elevation Model (DEM) of the McKenzie Creek watershed (shaded black) area. McKenzie Creek waterbody is in bolded blue, Boston Creek and the Grand River in light blue, McKenzie Creek flow station is represented by the blue dot and the York flow station by the red dot, and Six Nations of the Grand River boundary is outlined in black. **(B)** Map of Grand River watershed (shaded pink) with the McKenzie Creek watershed in shaded black, and Six Nations of the Grand River boundary outlined in black. Hamilton Airport is represented by the green dot.

The climate of the region is humid continental (Dfa/Dfb) with cold winters and hot/warm summers (Beck et al., 2018). Temperature conditions are somewhat milder due to its proximity to Lake Erie which has the warmest summer water among all Great Lakes (EPA, 2016). Land cover in the watershed consists of rural and agriculture (70%), forest (24%) wetland (<1%), and urban (<5%). The watershed contains Canada's largest block of Carolinian forest, primarily deciduous broad-leaf trees, which is located in the Six Nations area (MacVeigh et al., 2016). With respect to soil characteristics, the watershed is divided into Haldimand clay in the eastern part, Norfolk sand in the central and western part, and pockets of Wentworth till, and contains areas of gravel and exposed bedrock throughout. The coarser sand plains in the west of the watershed allow for greater infiltration of precipitation and groundwater recharge. Conversely, the clay plains in the central and eastern parts of the watershed (the majority of which is located in the Six Nations area) result in lower groundwater recharge rates and greater surface runoff, Overall, the hydrology of the watershed is strongly influenced by precipitation patterns (MacVeigh et al., 2016).

2.2 GSFLOW model

2.2.1 Model description

Simulations of hydrological processes and streamflow in the McKenzie Creek were performed using the Coupled Groundwater and Surface-Water Flow Model (GSFLOW) from 1951 to 2099. GSFLOW integrates two U.S. Geological Survey (USGS) models, the Precipitation-Runoff Modeling System (PRMS) and the Modular Groundwater Flow Model MODFLOW) to simulate surface and groundwater flow (Markstrom et al., 2008). The GSFLOW model has been previously used to simulate hydrological processes within the Grand River watershed (Earthfx, 2018) and has been used for climate change impact assessment for watersheds in the Great Lakes basin and other watersheds (Hunt et al., 2013; Feng et al., 2018; Soonthornrangsan and Lowry, 2021). A stand-alone PRMS has also been previously used to simulate hydrological processes within the Grand River and surrounding watersheds (Champagne et al., 2019; Champagne, 2020a; Champagne, 2020b). The GSFLOW model was chosen because it integrates surface processes computed by PRMS and groundwater simulations through MODFLOW, providing the Six Nations community with a holistic understanding of how climate change will affect the McKenzie Creek.

PRMS is a deterministic hydrological model used to simulate the response of precipitation, temperature and land use on a watershed. Streamflow is generated using hydrological components that are represented by algorithms based on a physical law or an empirical relation; the subsurface in PRMS is represented by the soil-zone and subsurface reservoirs (Markstrom et al., 2008). MODFLOW-2005 (also referred to as MODFLOW) is a finite-difference groundwater flow model, it simulates both steady state (i.e., constant flow velocity) and transient flow (i.e., altering flow velocity) water through porous Earth. Water entering and leaving the modelled saturated zone can be controlled through a number of processes including areal recharge, leakage to aquifers from streams and lakes, subsurface inflows, discharge by evapotranspiration from phreatophytes (i.e., plants with roots that reach the water table), discharge from pumping wells, and discharge to streams and lakes (Markstrom et al., 2008). Like all hydrological model GSFLOW has limitation and assumptions associated with it, for a detailed overview refer to Markstrom et al. (2008). Some of these limitations and assumptions include: 1-day timesteps and averaging of outputted flow thereby ignoring sub-daily extreme values, capillary reservoir being represented by a constant value of root depth for each HRU, and limited ability to simulate frozen ground conditions (Markstrom et al., 2008; Hunt et al., 2016).

2.2.2 Model set-up

In PRMS, the hydrological processes are computed for each HRU that has a surface grid cell size of 200 m × 200 m. PRMS allows for choice between different modules that were previously described in Champagne et al. (2019). The parameter values used by PRMS were spatialized to each HRU using Arcpy-GSFLOW under ArcGIS (Gardner et al., 2018), similar to what was previously done in several watersheds in the region by Champagne et al. (2019). MODFLOW has never been set up in this watershed before. For the MODFLOW, the horizontal grids were the same as the one used in PRMS (200 m × 200 m). In MODFLOW the vertical grids were discretized in 2 layers. The top layer represented the overburdened materials with a depth obtained by the Ontario Geological Survey (Gao et al., 2006). The deepest layer represented the bedrock with the surface corresponding to the bottom of the overburdened materials and the bottom fixed at 60 m. For each layer, the parameters needed in MODFLOW were estimated using the water wells data which provide the type of materials in the subsurface (for example, gravel, sand, silt, clay, etc.) (Ontario, 2021). The main subsurface material was coded from 1 to 4 from the largest grain (i.e., gravel) to the finest grind (i.e., clay). When several wells were present in a grid, the average soil characteristics for the code was calculated. If no well was present in the grid, the code was determined by interpolation of the surrounding averaged material codes. From these material codes, the spatial variability of hydraulic conductivity, specific yield and specific humidity were estimated per grid using literature values for each type of material (for example, gravel, sand, silt, clay, etc.) (Duffield, 2019).

Because agriculture is an important land use in the watershed, the well package (WEL) from MODFLOW was incorporated into GSFLOW's simulations to account for groundwater well extraction. The WEL package assigned a pumping rate to specific cells and pumping rates can be positive (injection) or negative (extraction). Based on McKenzie Creek data from Wong (2011) pumping rates of 9,298 ft^3 day^{-1} (263 m^3 day^{-1}) and –4,649 ft^3 day^{-1} (131 m^3 day^{-1}; for mixed surface/groundwater wells) were used in our study. The stress period was defined from June 1st to September 20th to align with observed agricultural pumping records (Wong, 2011). It should be noted that water usage records in Wong (2011) for McKenzie Creek does not take into account water extraction within the Six Nations reserve, because such information was not available. As a result, the water extraction value used during the calibration, validation, and later simulations of the model are likely an underestimation of the true amount of well water being extracted within the watershed. This creates a level of uncertainty within the model that cannot be accounted for without a detailed survey of well water extraction within the Six Nations reserve which is not within the scope of this study. Similar comments regarding incomplete pumping records have been made by Tian et al. (2015).

2.2.3 Model simulations

Daily total precipitation (P_{tot}) and daily maximum and minimum temperatures (T_{max}, T_{min}) were used as input data for model simulations. Control period (1951–2020) simulations were forced with observed gridded meteorological data (NRCANmet, 1951–2013) from Natural Resources Canada (NRCAN) and Environment and Climate Change Canada (ECCC) meteorological data (2014–2020) retrieved from Hamilton International Airport (Meteorological Service of Canada, Weather Station ID: 6153193) (Hopkinson et al., 2011; McKenney et al., 2011). Hamilton International Airport is approximately 40 km northeast from the source of the McKenzie Creek.

Simulated historical (1951–2020) and future (2021–2099) climate data were downscaled precipitation and temperature values from eleven global climate models (GCM) of the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Brekke et al., 2013) (Table 1). CMIP5 data before 2006 used observed GHG data, and CMIP5 data from 2006 onwards used projected GHG under RCP 4.5 and 8.5 scenarios. RCP 4.5 is an intermediate climate change pathway in which carbon dioxide (CO_2) emissions will continue to increase until the mid-21st century after which emissions begin to level out, while RCP 8.5 represents a high climate change pathway in which CO_2 emissions will continue to increase throughout the 21st century (Van Vuuren et al., 2011). Recent climate warming trends have been following the trajectory of RCP 8.5 (Schwalm et al., 2020). Downscaling of the CMIP5 GCMs was performed as outlined by Brekke et al. (2013) using the Bias Corrected Spatial Disaggregation (BCSD) method, which is a combination of 1) a bias correction technique using the quantile maps and 2) a spatial disaggregation of temperature and precipitation from the GCM grid resolution to 1/8° grid resolution (Brekke et al., 2013). Downscaled, bias-corrected GCM data have been previously used for climate change impacts studies as well as for watershed level studies (Navarro-Racines et al., 2020; Livingston et al., 2021). Despite this there are limitations in using GCM data to project future streamflow. Sources of uncertainty in CMIP5 data include natural internal climate variability, model uncertainty, and emissions scenario uncertainty (Barrow and Sauchyn, 2019).

2.2.4 Model calibration and validation

Calibration of GSFLOW was conducted from October 1998 to September 2003 and validated from October 2003 to September 2008 using Water Survey of Canada (WSC) observed streamflow from the McKenzie Creek near Caledonia (station number 02GB010). Approximately 25% of the observed streamflow data is classified as either a partial observation (i.e., calculation for daily data was made with an incomplete daily record), ice observation (i.e., ice cover was observed at the time of measurement), or estimated (i.e., observation is only an estimate). Consequently, uncertainties are introduced into the calibration of the model.

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TABLE 1 Climate model data used in the study.

Modelling center	Model name
Institute Pierre Simon Laplace Model (CM5A-LR)	IPSLCM5ALR
Russian Institute for Numerical Mathematics Climate Model (v4)	INMCM4
Model for Interdisciplinary Research On Climate (v5)	MIROC
National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory, Earth System Model	GFDLESM2M
	GFDLESM2G
Commonwealth Scientific and Industrial Research Organization	CSIRO
Centre National de Recherches Meteorologiques, Coupled Global Climate Model (v5)	CNRMCM5
Community Climate System Model (v4)	CCSM4
Canadian Centre for Climate Modelling and Analysis, Earth System Model (v2)	CanESM2
Beijing Climate Center, Climate System Model	BCCCSM
Australian Community Climate and Earth System Simulator	ACCESS

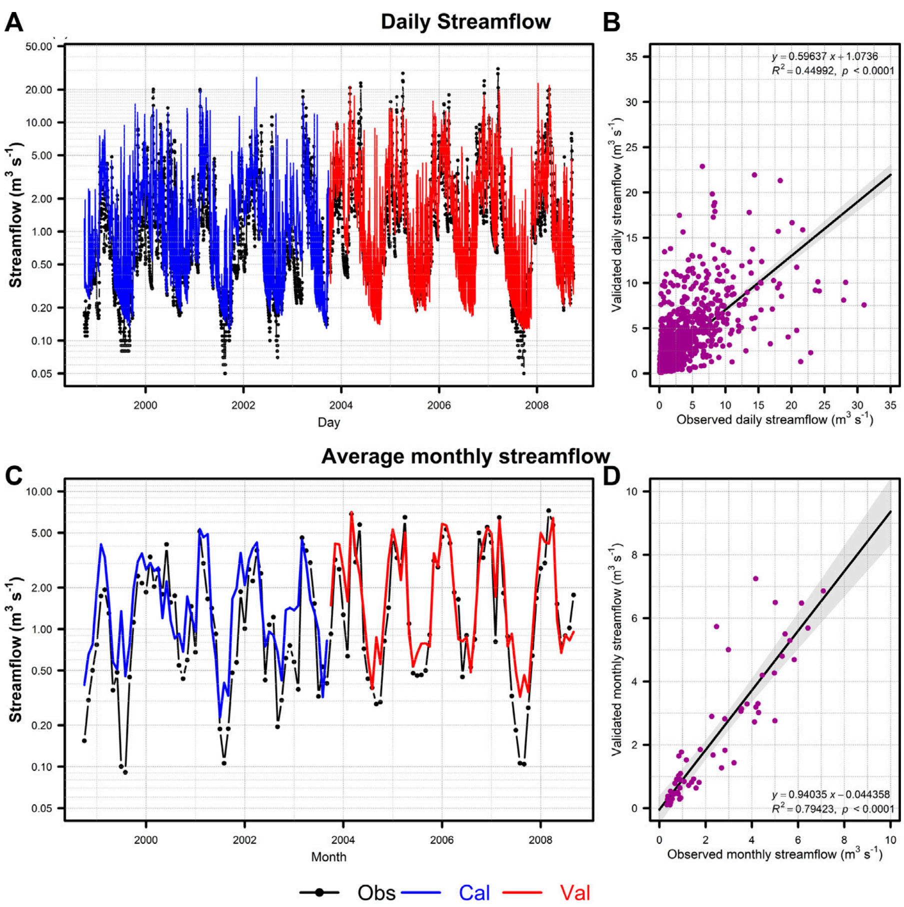

FIGURE 2
Calibration (October 1998–September 2003) and validation (October 2003–September 2008) results of GSFLOW streamflow simulations. **(A)** Daily observed and simulated streamflow, and **(B)** scatter plot of daily validation data against observed data during the validation period. **(C)** Monthly average of daily observed and simulated streamflow, and **(D)** scatter plot of monthly validation data against observed data during the validation period. Observed (Obs) streamflow is represented by the dashed-dotted black line, calibrated (Cal) streamflow is represented by the solid blue line, and validated (Val) streamflow is represented by the solid red line.

TABLE 2 Goodness-of-fit of calibration (October 1998–September 2003) and validation (October 2003–September 2008) period for results at a daily and monthly timesteps.

Time		NSE	RMSE	PBIAS	KGE	R^2
Daily	Calibration	−0.08*	2.23	29.3*	0.44	0.28*
	Validation	0.40*	2.56	8.2	0.64	0.6 (0.45)
Monthly	Calibration	0.40*	0.94	29.3*	0.62	0.61*
	Validation	0.78	0.94	8.5	0.85	0.79

Note. Unsatisfactory values are highlighted using *. Unweighted R^2 value is given in parenthesis. Evaluation criteria for NSE, PBIAS, and R^2 is based on Moriasi et al., 2015.

Calibration and validation simulations were performed on the Shared Hierarchical Academic Research Computing Network (SHARCNET) a shared supercomputer system among some Canadian universities. Due to time limitations on the network, 5-year calibration and validation periods were used to ensure that a sufficient number of model runs could be performed. The range of parameters for initialization and the optimal values obtained are shown in Supplementary Table S1. Optimal values were achieved using the Optimization Software Toolkit for Research Involving Computational Heuristics (OSTRICH) optimization algorithm, OSTRICH has previously been used to calibrate GSFLOW in other Canadian watersheds (Matott, 2017; Kompanizare et al., 2018).

Because this study focuses on long-term changes in McKenzie Creek, therefore, several commonly used goodness-of-fit statistical tests were performed on daily and monthly time scales to access model performance such as Nash-Sutcliffe efficiency (NSE), Root Mean Square Error (RMSE), Percentage Bias (PBIAS), Kling-Gupta efficiency (KGE), and coefficient of determination (R^2) (Moriasi et al., 2007; Moriasi et al., 2015). Daily and monthly calibration and validation results are shown in Figure 2 and summarized in Table 2. The goodness-of-fit statistical results are 0.78 (NSE), 0.94 (RMSE), 8.5 (PBIAS), 0.85 (KGE), and 0.79 (R^2) for monthly validation averages. Figure 2 shows that the model does well in simulating peak and low streamflow. The dip in late 2007 observed streamflow is due to extreme drought as reported by the Canadian Drought Monitor. Based on the goodness-of-fit statistics it can be inferred that the model's performance is satisfactory at monthly timesteps.

2.3 Water availability assessment

Canadian Drought Monitoring Services data indicates that between 2002 and 2022 there were 152 months defined as abnormally dry (event occurring once every 3–5 years), 77 moderate drought months (events occurring every 5–10 years), 33 severe drought months (events occurring every 10–20 years), and 8 extreme drought months (events occurring every 20–25 years) in Southern Ontario (Agriculture and Agri-Food Canada, 2022). Data also shows that the number of months with drought conditions has increased each year since 2002. A global assessment of compound drought-heatwave events (CDHW) found that under high emissions scenario CDHW will increase ten-fold, and regional results indicate that both the frequency and severity of CDHW will increase in the South Ontario region (Yin et al., 2023). Droughts have a significant impact on watersheds and the communities that rely on them for ecosystem services like agricultural irrigation. Water availability (W) was used to understand precipitated water that is not removed through evapotranspiration. This is water that can be stored as soil moisture, in underground aquifers, or runoff into streams or other water bodies; low water availability suggests the potential for dry or drought periods. Water availability was calculated using the water balance Eq. 1.

$$W = P_{tot} - ET \tag{1}$$

Where, P_{tot} is daily total precipitation (mm) and ET is daily total evapotranspiration (mm) simulated using GSFLOW.

3 Results

3.1 Climatic changes

Time series of annual values of observed and projected P_{tot}, T_{max} and T_{min}, are shown in Figure 3. From 1961 to 2020 mean observed P_{tot} was 886 mm year^{-1} and had a positive Sen's slope of 1.9 mm year^{-1}. During the same period projected mean P_{tot} for RCP 4.5 (RCP 8.5) warming scenario was 904 (906) mm year^{-1} and had a positive Sen's slope of 0.9 (0.9) mm year^{-1}. Future projections were divided into long-term averages; 2021–2039 (2020s), 2040–2069 (2050s), and 2070–2099 (2090s). P_{tot} is projected to increase from 947 (953) mm year^{-1} over the 2020s to 968 (980) mm year^{-1} over the 2050s, and 975 (1,008) mm year^{-1} over the 2090s period for RCP 4.5 (RCP 8.5). The rate of change in P_{tot} during those same periods is suggested to be 0.3 (0.5) mm year^{-1}, 0.6 (0.6) mm year^{-1}, 0.7 (3.1) mm year^{-1} under RCP 4.5 (RCP 8.5). Temperature has also increased throughout the 20th century. Mean T_{max} will increase from 14.6°C (17.7°C) during 2020s to 15.5°C (16.3°C) during 2050s, and 16.1°C (18.5°C) during 2090s for RCP 4.5 (RCP 8.5) scenario. Similarly, mean T_{min} will increase from 4.8°C (4.9°C) during 2020s to 5.7°C (6.5°C) during 2050s, and 6.2°C (8.4°C) during 2090s for RCP 4.5 (RCP 8.5).

Seasonal climatic changes in the watershed were also assessed using monthly P_{tot}, T_{max} and T_{min} anomalies (relative to 1961–1990 average) (Figure 4). Between 1961 and 2020 climate was characterized by low observed P_{tot} in January, February, and March compared to the other months (Figure 4A). With respect to future P_{tot}, simulations indicate that winter and spring P_{tot} will increase throughout the 21st century while summer and fall P_{tot} will remain unchanged or decrease under RCP 4.5 warming scenario (Figure 4C). Similar trends were also projected under RCP

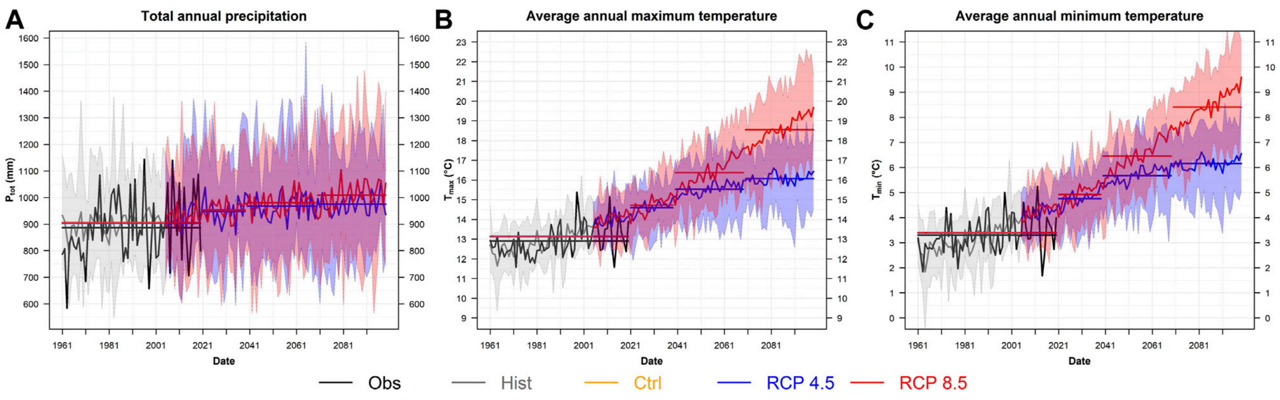

FIGURE 3
Annual average of daily McKenzie Creek watershed for **(A)** total annual precipitation (P_{tot}), **(B)** average annual maximum temperature (T_{max}), **(C)** average annual minimum temperature (T_{min}). Solid black lines are observed data, solid grey lines are historical data, the solid blue lines are averaged RCP 4.5 data, and solid red lines are averaged RCP 8.5 data. Multi-model range is represented by the shaded area, and horizontal lines are averages from 1961–2020 for observed, historical (1961–2005 historical + 2006–2020 RCP simulations), and control streamflow, and 2020s (2021–2039), 2050s (2040–2069), and 2090s (2079–2099) for RCP 4.5 and 8.5.

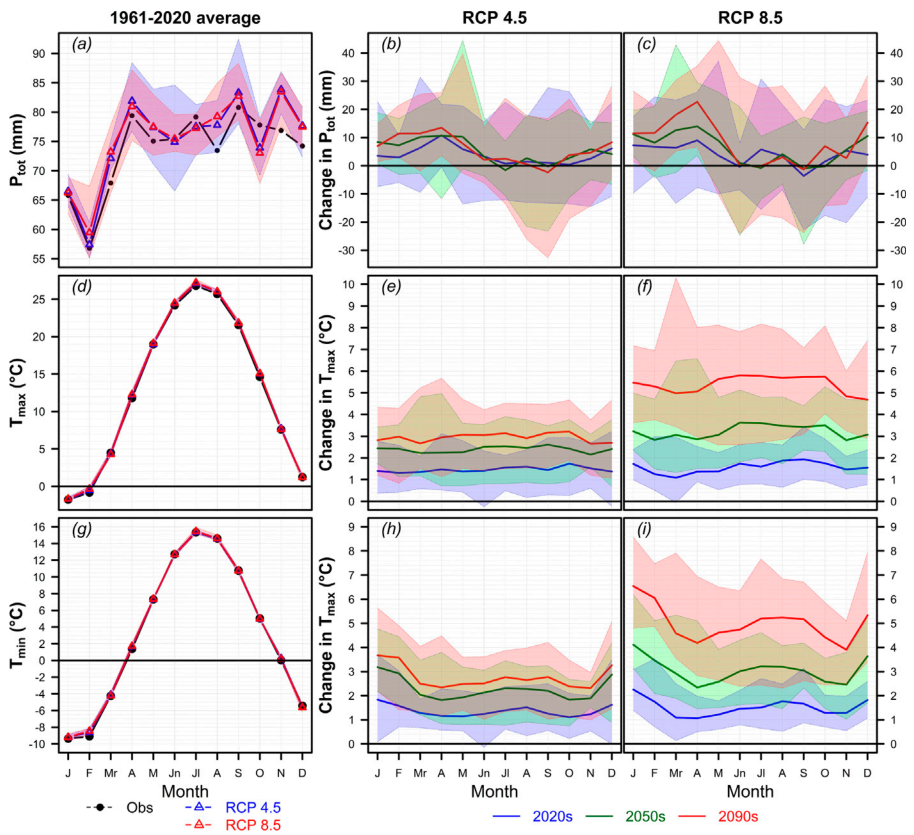

FIGURE 4
Changes in McKenzie Creek watershed's climate; anomalies were calculated relative to a 1961–2020 average. **(A)** Total precipitation (P_{tot}) baseline average, **(B, C)** P_{tot} anomaly, **(D)** maximum temperature (T_{max}) baseline average, **(E, F)** T_{max} anomaly, **(G)** minimum temperature (T_{min}) baseline average, and **(H–I)** T_{min} anomaly. Dashed solid-dotted black lines are observed (Obs) values, and historical (Hist) values are dashed open-triangle blue (RCP 4.5) and red (RCP 8.5) lines between 1961–2020. Solid blue lines are future values for the 2020s (2021–2039), solid green lines are future values for the 2050s (2040–2069) and solid red lines are future values for the 2090s (2070–2099). Multi-model range is represented by the shaded area.

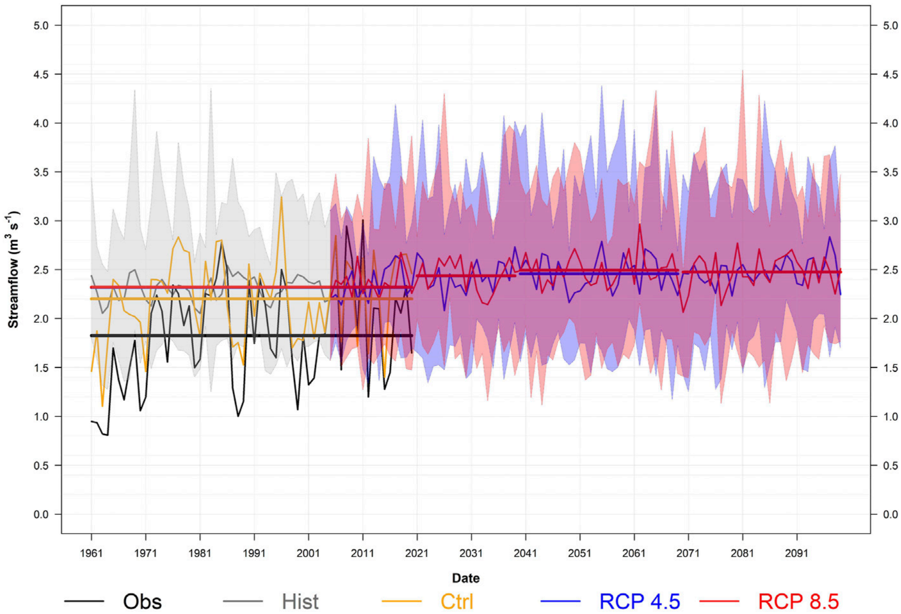

FIGURE 5
Annual average of McKenzie Creek streamflow. Solid black lines are observed data, solid grey lines are historical data, the solid yellow line is controlled data, solid blue lines are averaged RCP 4.5 data, and solid red lines are averaged RCP 8.5 data. Multi-model range is represented by the shaded area, and horizontal lines are averages from 1961–2020 for observed, historical (1961–2005 historical + 2006–2020 RCP simulations), and control streamflow, and 2020s (2021–2039), 2050s (2040–2069), and 2090s (2079–2099) for RCP 4.5 and 8.5.

8.5 warming scenario, however with relatively higher P_{tot} values (Figure 4D). T_{max} and T_{min} are projected to increase under both RCP 4.5 and RCP 8.5, with late spring and summer months seeing the greatest increase in T_{max} and winter months seeing the greatest increase in T_{min} (Figures 4E-F and H-I).

3.2 Annual changes in McKenzie Creek watershed

Study results showed that mean annual streamflow in the McKenzie Creek has increased over time (Figure 5). From 1961 to 2020, observed streamflow increased from 0.95 to 1.64 $m^3 s^{-1}$ (167.9–291.9 mm $year^{-1}$) indicating a rate of increase of 0.01 $m^3 s^{-1}$ (2.1 mm $year^{-1}$). Mean streamflow over this period was 1.82 $m^3 s^{-1}$ (323.6 mm $year^{-1}$). Over the same period, simulated past streamflow (control run) increased from 1.5 to 2.5 $m^3 s^{-1}$ (259.4–436.2 mm $year^{-1}$) indicating a rate of increase of 0.005 $m^3 s^{-1}$ (0.85 mm $year^{-1}$). Mean control streamflow during this period was 2.2 $m^3 s^{-1}$ (390.2 mm $year^{-1}$). Based on Mann-Kendall (MK) tests, all observed, control and historic streamflow values showed an upward trend between 1961 and 2020. Although these upward streamflow trends are not statistically significant at the annual timescale, they were statistically significant at daily timescales. This increasing trend in streamflow is projected to continue until the end of the 21st century for both RCP 4.5 and RCP 8.5 scenarios. However, this future projected increase will be steady over time with a Sen's slope of 0.00083 $m^3 s^{-1}$ (0.14 mm $year^{-1}$) for RCP 4.5 and 0.00072 $m^3 s^{-1}$ (0.13 mm $year^{-1}$) for RCP 8.5. Study results further indicated that the rate of increase in mean annual streamflow will remain steady at 2.4 $m^3 s^{-1}$ during the 2020s, 2050s, and 2090s for both RCP 4.5 and 8.5, with exception of RCP 8.5 streamflow during 2050s which will be slightly higher than RCP 4.5 streamflow.

3.3 Seasonal changes in McKenzie Creek watershed

Time series of mean monthly values of observed and control streamflow from 1961 to 2020 are shown in Figures 6A–E. Seasonal observed streamflow within the watershed is characterized by peaks in March with a slight decline in April, and low flows in June through September. Relative to the 1960s, observed decadal mean streamflow in all seasons experienced an increase. Mean peak flow in 1960s was 3.4 $m^3 s^{-1}$, which increased to 6.6 $m^3 s^{-1}$ in the 1970s and remain steady between 3.8 and 4.8 $m^3 s^{-1}$ in the following decades. In control runs, GSFLOW model was able to reproduce the overall seasonal dynamics of observed streamflow, but with some overestimation. Control streamflow was best reproduced during the 1970s, 1980s, and 2010s when compared to observed values.

Simulated monthly streamflow values for the future until the end of the 21st century are shown in Figure 7. Future streamflow simulations under both RCP 4.5 and RCP 8.5 scenarios suggest an increase in winter (December, January, February) streamflow as compared to historical streamflow from 1961–2020 (Figure 7A). However, while winter streamflow will continue to increase throughout the 21st century, its rate of increase will decline over time with the largest increase occurring between 2020s and 2050s. With respect to spring months, future mean streamflow will

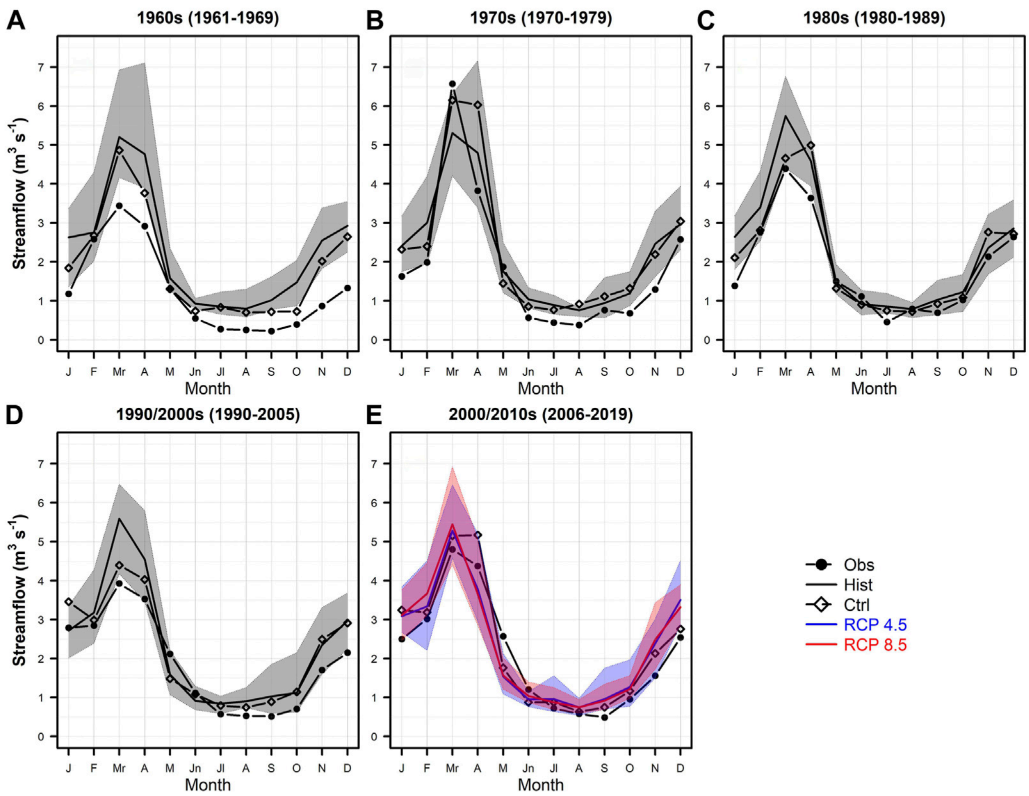

FIGURE 6
Monthly average of daily McKenzie Creek streamflow by decade for **(A)** 1960s (1961–1969), **(B)** 1970s (1970–1979), **(C)** 1980s (1980–1989), **(D)** 1990/2000s (1990–2005), and **(E)** 2000/2010s (2006–2019). Dashed solid-dotted black lines are observed (Obs) values, dashed open-dotted black lines are controlled (Ctrl) values, solid black lines are historical (Hist) values, and solid blue (RCP 4.5) and solid red (RCP 8.5) lines for simulated values. Multi-model range is represented by the shaded area.

decrease by 8.7% (RCP 4.5) and 13.0% (RCP 8.5) by the end of the century (Table 3) as compared to observed/historical mean streamflow. April will experience the largest decrease with −13.3% (RCP 4.5) to −18.2% (RCP 8.5) decline. Furthermore, mean summer and autumn streamflow is projected to experience no change relative to the historical seasonal values. However, summer streamflow will increase over the three future time periods (i.e., 2020s, 2050s, and 2090s).

In addition to streamflow, the model also simulated other hydrological processes such as evapotranspiration (*ET*) (Figures 8A–C) and the volume of water in the snowpack (Figures 8D–F). *ET* between 1961 and 2020 is characterized by high *ET* values from late spring to the end of summer, with peak *ET* values in May. Both RCP 4.5 and 8.5 showed an increase in mean *ET* in all seasons (except summer of 2090s under RCP 8.5) relative to mean *ET* values in 1961–2020. This increase is projected to be highest in the winter and smallest in the summer. For example, peak *ET* in May is projected to increase by 7.3% (4.6%), 10.8% (10%), and 10.7% (13.2%) during the 2020s, 2050s, and 2090s for RCP 4.5 (RCP 8.5) scenario.

Within the McKenzie Creek watershed snowpack accumulation has historically occurred between late October and early May with January, February, and March having the largest amount of snowpack (Figures 8D–F). During the 21st century the volume of water present in McKenzie Creek watershed as snowpack will decrease. Under RCP 4.5 scenario average winter snowpack will decrease by 28.8% (2020s), 50.6% (2050s), and 54.3% (2090s), relative to 1961–2020 winter averages, while March snowpack volume will decrease by 46%, 69.7%, and 73.8%. Under RCP 8.5 average winter snowpack volume will decrease by 39.3%, 61.8%, and 81.9%, relative to historical winter average, and March snowpack volume will decrease by 49.1%, 78.8%, and 92.9%.

3.4 Water availability

Within the McKenzie Creek watershed the availability of water (P_{tot}—ET) is positive throughout the year, except for May when monthly *ET* is greater than monthly P_{tot}, resulting in a negative water balance (Figure 9). Future projections suggest that seasonal water availability will increase under both RCP 4.5 and RCP 8.5 scenarios except during fall, as well as spring 2090s under RCP 8.5. By the end of the century (2090s) mean winter water availability is projected to increase by 10.9% (RCP 4.5) and 7.7% (RCP 8.5), relative to 1961–2020 period. Average spring water availability will not change under RCP 4.5 but decrease by 18.7% under RCP 8.5, while initially increasing in 2020s and 2050s. Mean fall water availability will decrease consecutively by 2.4% (2.4%), 2.4% (2.4%), and 4.1% (9.5%) during the three future periods under RCP 4.5 (RCP 8.5). Summer water available will remain low

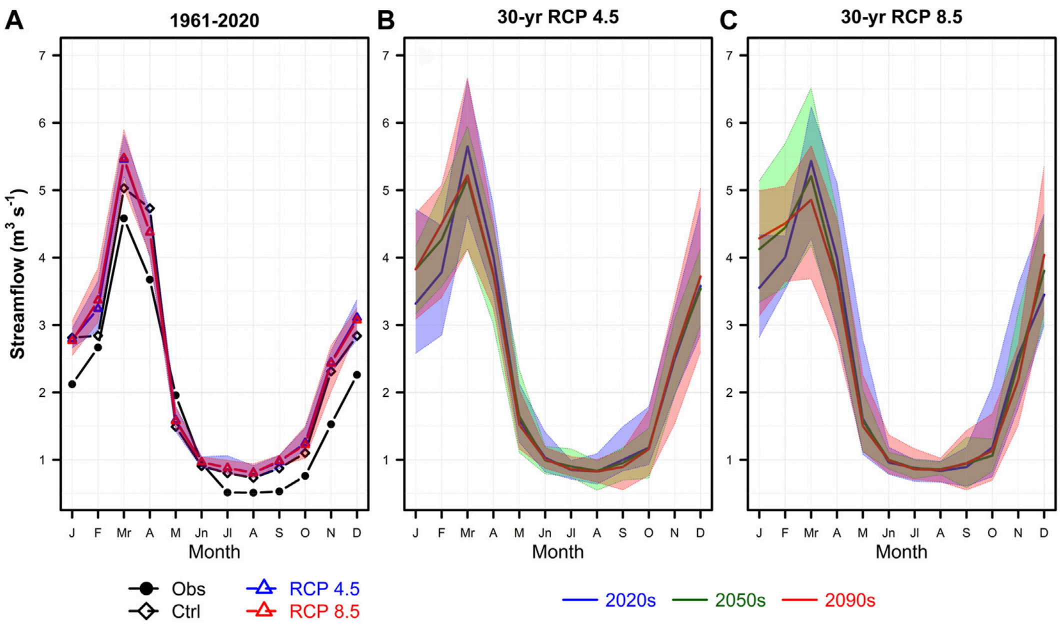

FIGURE 7
Long-term monthly average of daily streamflow. **(A)** Streamflow from 1961–2020, where dashed-dotted black lines are observed (Obs) values, dashed open-dotted black lines are control (Ctrl), and historical (Hist) values are dashed open-triangle blue (RCP 4.5) and red (RCP 8.5) lines between 1961–2020. And **(B)** RCP 4.5 and **(C)** 8.5 where solid blue lines are future values for the 2020s (2021–2039), solid green lines are future values for the 2050s (2049–2069) and solid red lines are future values for the 2090s (2070–2099). Multi-model range is represented by the shaded area.

TABLE 3 Simulated average seasonal streamflow values for 2020s (2005–2039), 2050s (2040–2069), and 2090s (2070–2099) shown as percentage change relative to 1961–2020 baseline period for two greenhouse gas emission scenarios, IPCC RCP 4.5 and RCP 8.5.

	RCP 4.5			RCP 8.5		
	2020s	2050s	2090s	2020s	2050s	2090s
Winter	17.6%	27.5%	31.9%	18.3%	32.3%	37.6%
Spring	−2.6%	−8.7%	−8.7%	−4.3%	−8.7%	−13.0%
Summer	−3.7%	0.0%	0.0%	0.0%	3.7%	0.0%
Autumn	2.2%	4.3%	2.2%	0.0%	−4.3%	−6.5%

Note: Winter (December, January, February); Spring (March, April, May); Summer (June, July, August) and Autumn (September, October, November).

throughout the 21st century with very little change projected. Comparison between the three future time periods suggests that summer water availability will not change under RCP 4.5 and only by 0.2–0.3 mm under RCP 8.5.

4 Discussion

4.1 Streamflow

Our study results showed that the increase in observed mean annual streamflow in the McKenzie Creek is in line with other streamflow observations made in the region. A trend analysis of streamflow within the Great Lakes basin found that 71 U.S. Geological Survey (USGS) and 22 Environment and Climate Change Canada (ECCC) flow stations experienced an upward trend between 1960–2015 (Norton et al., 2019). Changes in observed seasonal patterns of P_{tot} (predominantly winter increase) are the likely cause of increasing winter streamflow within the McKenzie Creek (Figures 7A–C). These are consistent with reported long-term impacts of climate change on streams within the Grand River watershed. Such as Azarkhish et al. (2021) who found that the Nith River, another sub-watershed in the southern portion of the Grand River, experienced a significant increase in January streamflow and a significant decrease in March streamflow between 1973 and 2017. These changes in seasonal streamflow are likely associated with the warming of the atmosphere, causing earlier snowmelt and higher winter precipitation. However, large-scale climate variabilities modes, such as El Niño–Southern Oscillation (ENSO) and North

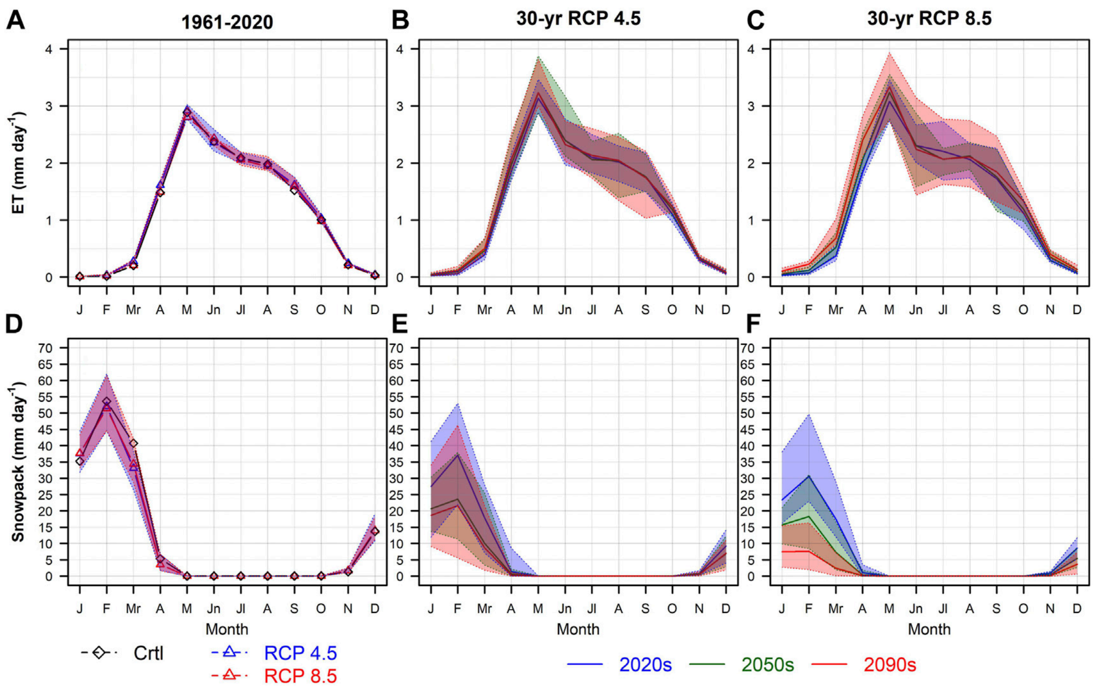

FIGURE 8
(Top row) Monthly average of daily volumetric flow rate of evapotranspiration from pervious areas (*ET*) within the McKenzie Creek watershed. **(A)** Average historical *ET*, and future average *ET* under **(B)** RCP 4.5 and **(C)** 8.5. (Bottom row) Monthly average of daily volume of water in snowpack storage within the McKenzie Creek watershed. **(D)** Average historical snowpack volume, and future average snowpack volume under **(E)** RCP 4.5 and **(F)** 8.5. Dashed open-dotted black lines are controlled (Ctrl) values, and historical values are dashed open-triangle blue (RCP 4.5) and red (RCP 8.5) lines between 1961–2020. Solid blue lines are future values for the 2020s (2006–2039), solid green lines are future values for the 2050s (2049–2069) and solid red lines are future values for the 2090s (2070–2099). Multi-model range is represented by the shaded area.

Atlantic Oscillation (NAO), have also been found to influence streamflow in Canada (Fu et al., 2012; Nalley et al., 2019), and may be linked to inter-decadal changes in streamflow and precipitation in the region. For example, Shabbar et al. (1997) found that the first winter following El Nino event resulted in negative precipitation anomalies in the Great Lakes region. Also, Champagne et al. (2019) studied the effect of changes in atmospheric circulation on four watersheds in Southern Ontario and found that an increase in the frequency of high pressure systems in eastern North-America accounted for 40% of the increase in winter streamflow. The remaining change was likely associated to atmospheric warming. Other anthropogenic factors may have also influenced changes in streamflow in McKenzie Creek such as land cover change (Buttle, 2011), and water use and management practices throughout the 20th century.

With respect to future projections, both RCP 4.5 and RCP 8.5 scenarios suggest that streamflow will increase in winter, decrease in spring, and experience little to no change in summer and autumn. Projected seasonal precipitation will follow similar trends. Increase in winter streamflow will likely be due to the increase in winter precipitation, and warmer winter temperatures causing a decrease in water storage in snowpack in the watershed. Decreased water storage in snowpack storage is also likely the cause of projected peak streamflow decreases in March because of less winter-spring snowmelt. Future streamflow patterns in the McKenzie Creek are similar to other hydrological modelling studies in other watersheds in the region. For example, Li et al. (2016) found that the Grand River streamflow will likely increase during winter months and decrease in the summer under SRES A2 (high level warming scenario) and B2 (mid-level warming scenario). Under RCP 4.5 and RCP 8.5 scenarios Zhang et al. (2018) found that future streamflow in the Grand and Thames rivers will increase in winter and decrease in spring. Similarly, Champagne et al. (2020a) found that winter (January-February) streamflow in the Grand River will increase by about 30% between 2026 and 2050 under RCP 8.5.

4.2 Flooding

Flooding has historically been the most common type of hydrometeorological hazard to occur in Canada, (Public Safety Canada, 2022), and has resulted in billions of dollars in damages and hundreds of deaths (Buttle et al., 2016). In the Great Lakes region, including Southern Ontario, flooding has been dominated predominantly by snowmelt, rain-on-snow followed by ice-jams, heavy spring rainfall and summer storms (Buttle et al., 2016). Burn and Whitfield (2016) found that between 1961 and 2010 the frequency and duration of flood events in Southwestern Ontario not only increased in frequency but also occurred earlier in the year. Cunderlik and Ouarda (2009) reported similar findings for snowmelt induced flooding events which occurred earlier in the region. Additionally, Rokaya et al. (2018) found that between

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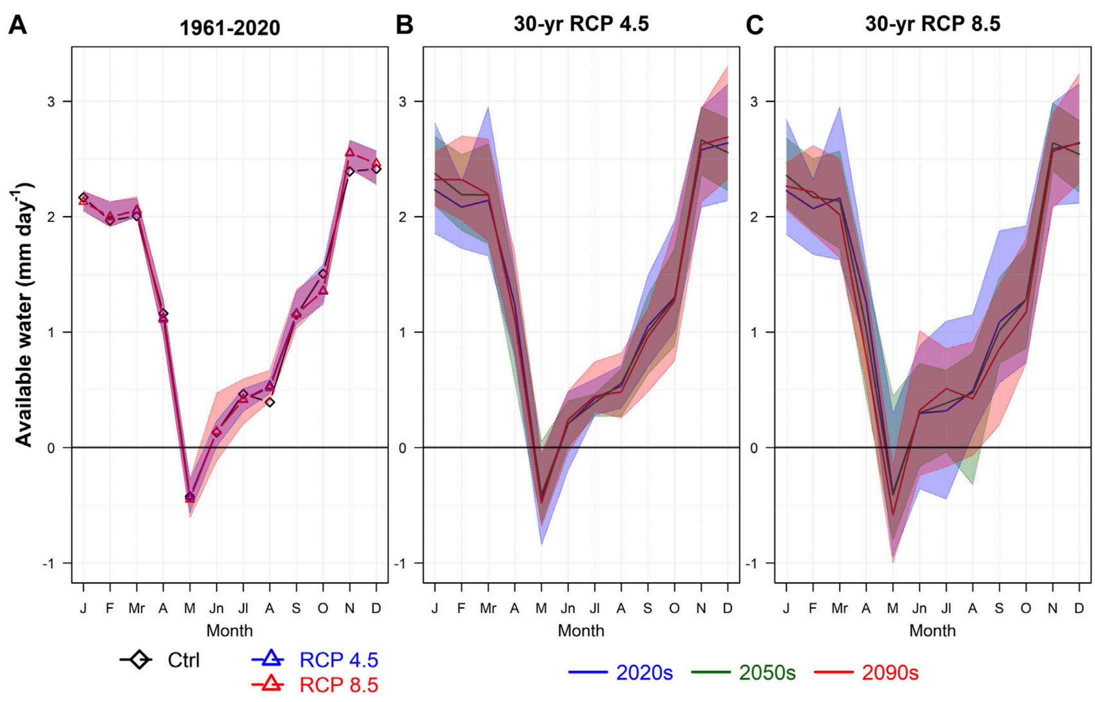

FIGURE 9
Monthly average of daily available water within McKenzie Creek watershed. **(A)** Average controlled and historical monthly average of available water, and future monthly average of available water under **(B)** RCP 4.5 and **(C)** 8.5. Dashed open-dotted black lines are controlled values, and historical values are dashed open-triangle blue (RCP 4.5) and red (RCP 8.5) lines between 1961–2020. Solid blue lines are future values for the 2020s (2006–2039), solid green lines are future values for the 2050s (2049–2069) and solid red lines are future values for the 2090s (2070–2099). Multi-model range is represented by the shaded area.

1903 and 2015 there was an earlier occurrence of ice-jams but an overall decrease in streamflow in the region. They also found that small unregulated basins were more sensitive to climate change, within the context of the timing of ice-jams.

Our study results provide vital information about the potential changes in future flooding events within the McKenzie Creek watershed. An earlier study of extreme climate events within the McKenzie Creek watershed projected that the annual frequency and intensity of extreme precipitation events will increase within the region (Deen et al., 2021). This, in combination with increased winter precipitation within the watershed, may cause earlier winter flooding in the McKenzie Creek. Due to the meandering nature of the McKenzie Creek as it passes through the eastern portion of the watershed, earlier winter flooding may increase the vulnerability of the Six Nations community. While flooding may occur earlier within the McKenzie Creek watershed, the intensity of March flooding will likely not increase as the volumetric water content of winter snowpack will decrease throughout the 21st century resulting in lower overall winter-spring snowmelt. This change is in line with similar findings, across Canada the timing of seasonal peak flow has changed with spring peak flow occurring earlier as a result of earlier snowmelt. Bonsal et al. (2019) suggest that these changes may result in earlier and more intense flooding events. Within Ontario it is projected that climate change will increase the frequency of flooding events, with historical 100-year events occurring more frequently (Gaur et al., 2018).

4.3 Water stresses

Our modelling study also provides insight into the occurrence of future dry conditions or droughts in the McKenzie Creek watershed. Drought conditions during the 20th century in Southern Ontario have been characterized by above normal annual temperatures and below normal precipitation (Klaassen, 2002). Within the McKenzie Creek watershed climate projections indicate that annual temperature will increase above annual normal levels, and seasonal precipitation will be below previous normal conditions (Figures 3B-C and 4B-C).

Given that our projections indicate low spring and summer streamflow along with increases in temperature, decrease in precipitation, and less soil moisture recharge from snowmelt, drought or water stress may become more prevalent during late spring and summer months in the watershed. Specifically, our water availability estimates show that late spring and summer experiences low water availability and May experiences negative water availability. Future increases in *ET* and seasonal temperature suggests greater evaporative water loss and potentially more water stress within the watershed. Similar trends have been projected for the wider Grand River watershed by Li et al. (2016). This may affect agricultural and ecosystem productivity of the McKenzie Creek watershed. However, drought or water stress impacts may be alleviated by an increase in groundwater recharge due to higher infiltration in winter months because of warmer temperatures and less freezing of soil as suggested by Jyrkama and Sykes (2007). This aspect should be the subject of future water security studies in a changing climate.

5 Conclusion

In this study the Coupled Groundwater and Surface-Water Flow Model (GSFLOW), an integrated surface runoff and groundwater hydrological model, was used to simulate historical (1951–2020) and future (2021–2100) streamflow under IPCC RCP4.5 and RCP 8.5 warming scenarios for the McKenzie Creek. The McKenzie Creek is a tributary of the Grand River watershed which provides water resources for the Six Nations of the Grand River reserve—the largest Indigenous community in Canada and the fourth largest in North America by population. Study results show that annual average observed, control (i.e., GSFLOW simulations using observed data), and historical (GSFLOW simulations using GCM downscaled data over the past observation period) streamflow have experienced an upward trend between 1961 and 2020. Similar increasing trends in future streamflow have also been simulated by the model under both RCP 4.5 and RCP 8.5 warming scenarios. With respect to changes in seasonal dynamics of streamflow, we found that in the future monthly streamflow will increase the most during winter months (January, February, and December) with a 31.9% (RCP 4.5) and 37.6% (RCP 8.5) change by 2090s. These seasonal changes are due to increasing winter temperatures and precipitation in the Great Lakes region. Average spring streamflow will decrease by 8.7% (RCP 4.5) and 13.0% (RCP 8.5) by 2090s. Summer and autumn streamflow will experience little change during the 21st century.

Our study results suggest the following impacts of climate change on the McKenzie Creek watershed as well as the communities living in this area of the Great Lakes due to climate change: 1) There will be potentially earlier winter flooding events in future due to increasing winter temperature and precipitation, 2) the intensity of flooding during peak streamflow in March will be less likely due to smaller winter snowpack, and 3) there will be a potential increase in summer dry periods or drought events due to increasing summer temperatures causing higher evaporative water loss and a decreasing trend in precipitation and streamflow. Overall, water availability in the watershed will continue to remain low in spring and summer periods causing water stress for the communities relying on this watershed. This would be despite the fact that overall, on an annual basis the watershed is expected to experience higher precipitation and higher annual streamflow in the future. The finding of this study can be used by Six Nation's environmental planners, and the community to better prepare for future impacts of climate change. Water resources managers should consider the effects of winter or early spring flooding and summer droughts on the water quantity and quality for the community. Apart from Six Nations, these finds would also be useful and guide other water resources managers, planners and communities in the Southern Ontario and eastern Great Lakes region and explore ways to adapt to water stress and water insecurity as climate change continues to intensify.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

TD wrote the original draft, and performed formal analysis and visualization of the data. The study design and methodology was developed by TD, OC, and MA. All authors including PC-F and DM-H provided insight and comments. MA, PC-F, and DM-H provided funding. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1171210/full#supplementary-material

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