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Blue and Green Water Scarcity in the McKenzie Creek Watershed of the Great Lakes Basin

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ABSTRACT

Climate change and extreme weather events affect hydrology and water resources in catchments worldwide. This study analysed Blue Water (*BW*) and Green Water (*GW*) scarcity in the McKenzie Creek watershed in Ontario, Canada, and explored how changes in temperature and precipitation may impact water scarcity dynamics. The McKenzie Creek is the main water source for agricultural activities for the Six Nations of the Grand River reserve (the largest Indigenous community in Canada) and other non-Indigenous communities in the watershed. Data from the water use surveys and streamflow simulations performed using the Coupled Groundwater and Surface-Water Flow Model (GSFLOW) under the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathways (RCP) scenarios 4.5 and 8.5, representing moderate and high greenhouse gas emissions and climate warming, respectively, were used to calculate *BW* and *GW* scarcity. Study results showed that *BW* scarcity may increase to 'moderate' levels if water users extract the maximum permitted water withdrawal allocation. This level of scarcity has the potential to cause ecological degradation and water quality issues in the watershed. *GW* scarcity will steadily increase throughout the 21st century due to climate warming with the western portion of the McKenzie Creek watershed projected to experience slightly higher levels of *GW* scarcity. This may cause users to withdraw more water resources, thereby decreasing *BW* available for downstream communities, including the Six Nations of the Grand River. This study provides water resource managers and regional planners with important information about potential challenges facing the watershed due to increased water use and changing climate conditions.

1 | Introduction

Many communities and regions across the world, including Canada, are experiencing water stresses due to climate change (Caretta et al. 2022; Carlson et al. 2021; Douville et al. 2021; ECCC 2013; NIC 2021; Sandhu, Weber, and Wood 2021; Wazneh, Arain, and Coulibaly 2019; Zadeh, Burn, and O'Brien 2020). These climate change-related water stresses are expected to further intensify in the future as suggested by the recent Intergovernmental Panel on Climate Change reports (e.g., IPCC 2023). Furthermore, it is estimated that 0.5–3.1 billion people may face water scarcity or insecurity in the coming decades (Gosling and Arnell 2016). Climate change is also expected to affect agricultural yields (Climate Risk Institute 2023). Additionally, Indigenous communities who rely heavily on the land for traditional living and resources (including water) would be impacted much more by climate change and resulting water scarcity (de Loë and Plummer 2010; Indigenous Services Canada 2024).

Addressing water-related issues (e.g., scarcity, risks) can be framed through a water security lens. Water security is a complex concept with many competing and overlapping definitions (Gerlak et al. 2018; Zeitoun et al. 2016), but it can be broadly defined as 'the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environments and economies' (Grey and Sadoff 2007). Multiple methods and indices are used to assess water security, for example, the Water Poverty Index (Sullivan 2002), the Falkenmark Water Stress Indicator (Damkjaer and Taylor 2017) and other water security indicators as outlined in Dickson et al. (2016). For catchment-level studies, Blue Water (*BW*) and Green Water (*GW*) have been used to assess water scarcity (Veettil and Mishra 2016; Mao et al. 2020; Giri, Arbab, and Lathrop 2018). *BW* refers to surface water in rivers, streams, lakes and ponds or groundwater that is available for human consumption, while *GW* is water from precipitation that is retained by the soil and is available for plant growth (Hoekstra et al. 2011). Water security assessments using *BW* and *GW* can help to better understand human and natural water uses, explore how they may be impacted by climate change and develop climate-tailored water management policies. Such an analysis is very critical for regions which are predominantly agricultural and/or have high population density, like the Great Lakes region in Canada and the United States. In the Great Lakes region, many studies have explored the impacts of climate change on ground and surface water, including the Grand River (Erler et al. 2019; Li et al. 2016), the Credit River (Philip et al. 2022), the Canard River (Rahman, Bolisetti, and Balachandar 2012), Western Lake Erie Basin (Pease et al. 2017), Upper Parkhill (Persaud et al. 2020) and Maumee watershed (Culbertson et al. 2016). Other studies have focused on water governance and Indigenous water issues (Collins et al. 2017; Plummer et al. 2013). These studies have underscored the vulnerability of watersheds and communities in the Great Lakes region to governance, extreme weather events and climate change. Often, climate change vulnerability is much higher for smaller watersheds because of their limited water storage capacity, higher sensitivity to temperature and precipitation changes and greater susceptibility to land use changes (Pilgrim, Cordery, and Baron 1982). In addition, climate vulnerability analysis and assessments can be challenging for smaller watersheds due to the absence or limited availability of relevant data (Tsegaw et al. 2020). For example, the Grand River watershed, the largest watershed in Southern Ontario, has 56 hydrometric stations (only 33 fully active) despite being comprised 93 subwatersheds (ECCC 2024).

This study explored how *BW* and *GW* resources may be affected by future climate change in the McKenzie Creek watershed in the Great Lakes region under the Intergovernmental Panel on Climate Change (IPCC), Representative Concentration Pathways (RCP) scenarios 4.5 and 8.5, representing moderate and high greenhouse gas emissions and climate warming (Van Vuuren et al. 2011). The McKenzie Creek is an important water and ecosystem service provider to farmers and communities in the lower portion of the Grand River, including the Six Nations of the Grand River reserve, which is the largest (by population) Indigenous community in Canada, and the seventh largest when compared to both Canada and the United States (Indigenous Services Canada 2020; MacVeigh, Zammit, and Ivey 2016; U.S. Census Bureau 2023). The Coupled Groundwater and Surface-Water Flow Model (GSFLOW; Markstrom et al. 2008), which integrates the Precipitation-Runoff Modelling System (PRMS; Markstrom et al. 2015) for surface water and Modular Groundwater Flow Model (MODFLOW; Harbaugh 2005) for subsurface water was used to perform past and future hydrologic simulations under RCP 4.5 and RCP 8.5 (Deen et al. 2023). The specific objectives of the study are to (i) determine and quantify changes in *BW* and *GW* usage under moderate (RCP4.5) and high (RCP8.5) future climate warming scenarios and (ii) explore how these changes in *BW* and *GW* may impact water use in different parts of the watershed.

This study will provide important information for the sustainable management of water resources and climate change adaptation planning in the McKenzie Creek watershed to ensure the water security of its communities. This information is especially important given the economic significance and population density of the region (EPA 2023).

2 | Methodology

2.1 | Site Description

The McKenzie Creek watershed is located in the southern portion of the Grand River watershed in the Lake Erie section of the Great Lakes Basin in Southern Ontario, Canada (Figure 1). It is managed and regulated by the Grand River Conservation Authority (GRCA). It covers an area of 194 km^2 and borders Brant County, Haldimand County and the Six Nations of the Grand River reserve (Six Nations). The McKenzie Creek flows from the west (highest elevation ~250 m above sea level) to the east (lowest elevation ~190 m above sea level) and joins the Boston Creek before discharging into the Grand River near Caledonia (MacVeigh, Zammit, and Ivey 2016). Discharge of the McKenzie Creek is 1.9 m^3s^{-1} (~350 mm m^{-2} $year^{-1}$ of runoff water of the watershed), which reduces to 0.9 m^3s^{-1} during the growing season (May–October) as shown by historical streamflow data from 1961 to 2020.

Agriculture is the dominant land cover in the watershed; however, there are large patches of Carolinian forest (predominantly broadleaf deciduous trees) in the Six Nations portion of the watershed (Figure 1c). The soil in the western portion of the watershed is sandy (Norfolk Sand Plains) with higher permeability, while the soil in the central and eastern areas of the watershed is predominantly clay (Haldimand Clay Plains) (Figure 1d,e). Land use and crop cover type in the McKenzie Creek watershed from 2011 to 2021 were estimated based on the Annual Crop Inventory (ACI) data, generated using optical (Landsat-8, Sentinel-2) and radar (RCM) satellite images with a spatial resolution of

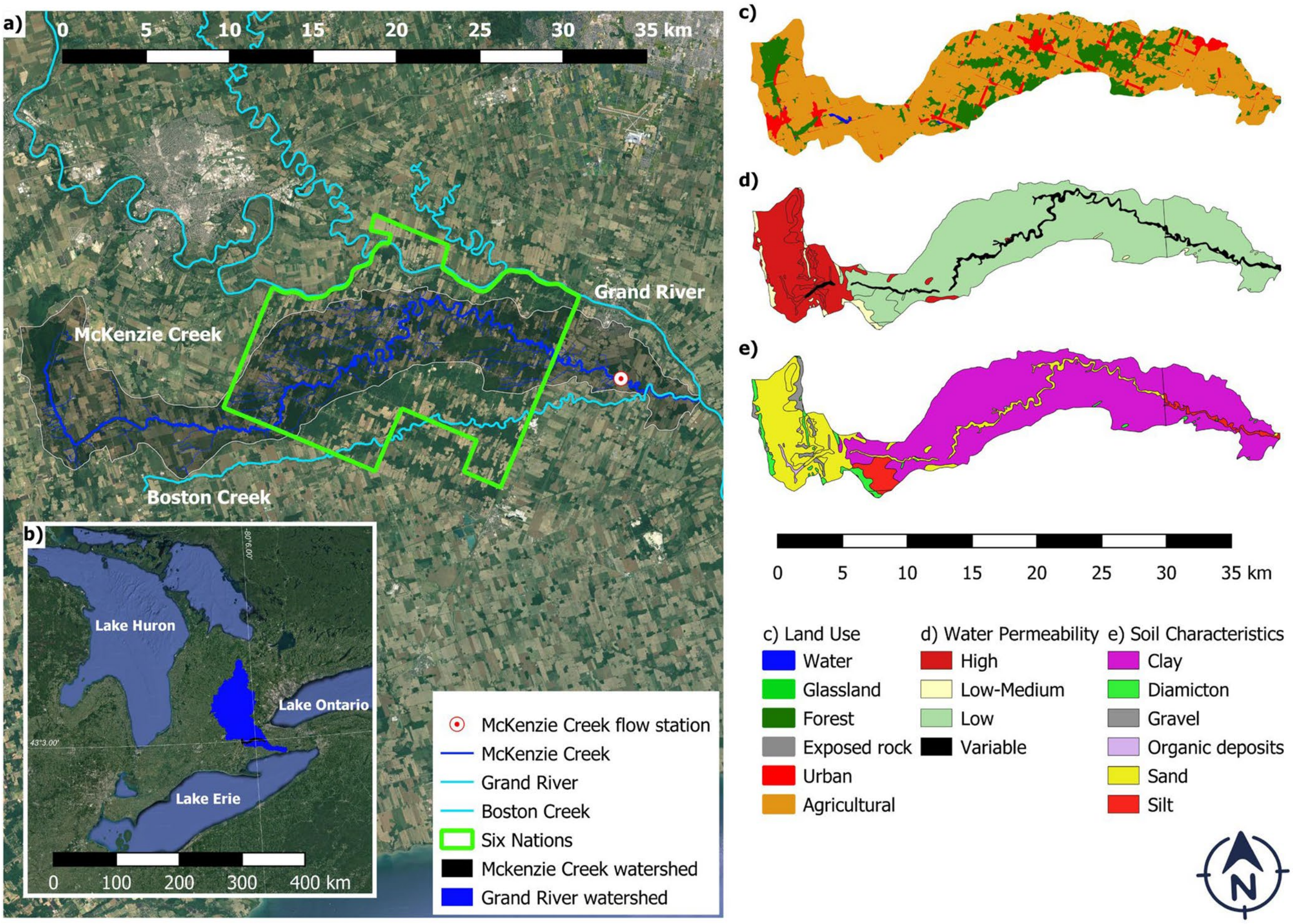

FIGURE 1 | (a) McKenzie Creek watershed with Six Nations area boundary and the location of McKenzie Creek, Boston Creek and Grand River overlain, (b) map of Grand River watershed and McKenzie Creek with surrounding Great Lakes, (c) land use classifications, (d) water permeability and (e) soil characteristics. Data adapted from GRCA (2023) and Ontario Ministry of Natural Resources and Forestry, MNRF (2014).

$30 \times 30\,m^2$ and a minimum of 85% accuracy (Agriculture and Agri-Food Canada 2023). Land use was categorised into several groups such as agricultural, forest (coniferous, broadleaf and mixed wood classifications), urban, natural lands (wetland, grassland, exposed land and 'too wet to be seeded' land classifications) and water. Agricultural land was further categorised into crop types (Table 1) following the Food and Agriculture Organisation's Indicative Crop Classification (ICC; FAO 2017).

The climate in the region is humid continental with warm/hot summers and cold winters (Beck et al. 2018). The mean total annual precipitation is 901 mm, and the mean annual temperature is 8.15°C as derived using data from Environment and Climate Change Canada (ECCC) weather station at Hamilton Airport from 1991 to 2020.

TABLE 1 | Land cover type classification in the McKenzie Creek watershed.

Crop type	Area (km^2)[a]	Description
Vegetables	41.21	Beans, peas, potatoes, soybeans, vegetables, other vegetables
Cereals	33.28	Wheat, winter wheat, spring wheat, corn, sorghum, barley, rye, oats, millets, cereals, buck wheat
Other	3.22	Ginseng, herbs, hops, orchards, sod, tobacco, nursery, greenhouse, other crops
Fruits	0.21	Berries, tomatoes, vineyards, fruits, other fruits
Oilseed	0.04	Canola, sunflower

[a]The land cover area estimates represent the average cover area from 2011 to 2021.

2.2 | Model Description

2.2.1 | GSFLOW Description and Setup

The Coupled Groundwater and Surface-Water Flow Model (GSFLOW, version 1.2.1) was used in this study to simulate past and future hydrological data which was then used for *BW* and *GW* estimations as outlined in Section 2.3. GSFLOW is an integrated hydrological model developed by the U.S. Geological Survey (USGS; Markstrom et al. 2015). It consists of the PRMS

(Markstrom et al. 2008) and the Modular Groundwater Flow Model (MODFLOW; Harbaugh 2005). PRMS is a deterministic hydrological model used to simulate surface and subsurface hydrological processes (e.g., streamflow, evaporation, transpiration, infiltration and more), while MODFLOW is a finite-difference groundwater flow model. PRMS and MODFLOW, both independently and when coupled as GSFLOW, have been widely used for hydrologic studies in Great Lakes watersheds, including the McKenzie Creek watershed (Deen et al. 2023) and the Grand River watersheds (Champagne, Arain, and Coulibaly 2019; Champagne et al. 2020; Champagne et al. 2020; Christiansen, Walker, and Hunt 2014; Earthfx 2018; Hunt et al. 2016; Feng et al. 2018; Soonthornrangsan and Lowry 2021; Teimoori et al. 2021).

GSFLOW integrates PRMS and MODFLOW by exchanging flow between three sources or regions. Region 1 is simulated using PRMS modules and includes the plant canopy, snowpack, impervious storage and soil zone. Region 2 includes streams and lakes, and region 3 is the subsurface (unsaturated and saturated zones) beneath the soil zone, both of which are simulated using MODFLOW. Flow is constantly moving between the regions, for example, groundwater discharge, leakage and gravity drainage. However, surface runoff and interflow only move in one direction within the model, that is, from region 1 to region 2.

In this study, GSFLOW model inputs were generated using the GSFLOW-Arcpy Python toolkit – GSFLOW-Arcpy which discretises datasets based on the physical characteristics (e.g., digital elevation model, geology and land use) into equally sized grids ($200 \times 200\,m^2$) for both PRMS and MODFLOW. To account for groundwater well extraction a water pumping rate was applied to GSFLOW using the Well (WEL) package. The water stress period was considered from June 1 to September 30. During this period water extraction from 52 groundwater wells, located primarily in the western portion of the watershed, was assigned as either $131\,m^3\,day^{-1}$ for mixed source (ground/surface water) extraction or $263\,m^3\,day^{-1}$ for groundwater-only well extraction (MacVeigh, Zammit, and Ivey 2016; Wong 2011). There were 35 groundwater wells and 17 mixed wells (surface and groundwater) in the watershed. To account for groundwater seepage to adjacent watersheds, the Flow and Head Boundary package (FHB) was used. Groundwater was lost at a rate of $29\,368\,m^3\,day^{-1}$ (MacVeigh, Zammit, and Ivey 2016), which was divided among the 125 MODFLOW grid cells that border surrounding watersheds resulting in a water seepage rate of $234.85\,m^3\,day^{-1}$ for each grid.

2.2.2 | Model Forcing Data

Daily minimum and maximum temperatures, and daily total precipitation for the past (1951–2005) and future (2006–2100) periods were used as forcing data in GSFLOW simulations at both grid- and basin-level. These forcing data were obtained from 11 downscaled Global Climate Models (GCM) under the Coupled Model Intercomparison Project Phase 5 (CMIP5) for both historical and future periods (Brekke et al. 2013). CMIP5 data from 1951 to 2005 used observed greenhouse gases (GHGs) data, while data from 2006 to 2099 used projected GHG data. Downscaling of the CMIP5 GCM data was performed using the Bias Corrected Spatial Disaggregation (BCSD) method, which is a combination of a bias correction technique using the quantile maps and a spatial disaggregation of temperature and precipitation from the GCM grid resolution of $2.5^o \times 2.5^o$ to downscaled grid resolution of $0.125^o \times 0.125^o$ (Brekke et al. 2013). Climate data accounted for future warming by using RCPs 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, 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). Control model simulations were performed from 1951 to 2020 using observed gridded meteorological data developed by Natural Resources Canada (NRCANmet) (Hopkinson et al. 2011; McKenney et al. 2011) and observed meteorological data from the Hamilton International Airport weather station (Meteorological Service of Canada, Weather Station ID: 6153193).

2.2.3 | Model Calibration and Validation

The GSFLOW model was calibrated from October 2003 to September 2008 and validated from October 2008 to December 2020 using daily observed streamflow data of the McKenzie Creek obtained from the Water Survey of Canada (WSC) for the 'McKenzie Creek near Caledonia' flow station (number 02GB010). Calibration was performed using the Dynamically Dimensioned Search (DDS) algorithm with the Optimization Software Toolkit for Research Involving Computational Heuristics (OSTRICH) (Matott 2017; Tolson and Shoemaker 2007). Optimal values were determined using the Weighted Sum of Squared Errors (WSSE) as the objective function with 20% perturbations of model parameters. OSTRICH and DDS have previously been used to calibrate GSFLOW (Kompanizare et al. 2018) and PRMS in the nearby Big Creek watershed (Champagne 2020). GSFLOW-simulated groundwater was not validated because the Provincial Groundwater Monitoring Network (PGMN) programme does not have data available for the McKenzie Creek watershed (MECP 2024). Daily and monthly calibration and validation results as well as goodness-of-fit statics are summarised in Table S1 and Figure S1. The evaluation criteria for Nash-Sutcliffe model efficiency coefficient (NSE), Percentage Bias (PBIAS) and coefficient of determination (R^2) are based on Moriasi et al. (2015). The goodness-of-fit statistical results for monthly average calibration (validation) simulations are 0.78 (0.59), 0.94 (1.26), 8.5 (17), 0.85 (0.72) and 0.79 (0.72) for NSE, root mean square error (RMSE), PBIAS, Kling-Gupta efficiency (KGE) and R^2, respectively. Monthly assessment of calibration and validation data has previously been done by Moriasi et al. (2007, 2015).

2.3 | Water Security Assessment

The study employed the water footprint assessment method outlined in Hoekstra et al. (2011), which utilises streamflow, evapotranspiration (ET) and soil water content to quantify *BW* and *GW* for the assessment of water scarcity.

2.3.1 | *BW* Scarcity

BW is fresh surface or groundwater used for human consumption or activities such as industrial, commercial or agricultural processes (Hoekstra et al. 2011). In this study, *BW* withdrawal was based on observed monthly water usage from 2007 to 2008 and 2012 annual permit data, which are the most recent water surveys of the McKenzie Creek (MacVeigh, Zammit, and Ivey 2016; Wong 2011). Because no observed groundwater extraction data were available to validate simulated groundwater by the model, this study only considered surface water withdrawal for agricultural use while estimating *BW* scarcity ($BW_{scarcity}$). It should be further noted that neither Wong (2011) nor MacVeigh, Zammit, and Ivey (2016) report on water withdrawals by the Six Nations' users; therefore, $BW_{scarcity}$ calculations should be considered underestimated.

Decreases in available *BW* ($BW_{available}$) and increases in water consumption, also referred to as *BW* footprint ($BW_{footprint}$), may increase $BW_{scarcity}$ in the watershed. $BW_{available}$ and $BW_{scarcity}$ were calculated as:

$$BW_{available} = Q - EFR \quad (1)$$

$$BW_{scarcity} = \frac{BW_{footprint}}{BW_{available}} \quad (2)$$

where *Q* is the monthly streamflow ($m^3 s^{-1}$) and EFR is the environmental flow requirements ($m^3 s^{-1}$), which is the amount of streamflow required to sustain the ecological health of the watershed. There are several ways to calculate EFR such as the presumptive standard method (PSM), 7-day 10-year low flow (Q7,10) and the Tennant and Tessmann methods, among others (Karakoyun, Dönmez, and Yumurtacı 2018; Rodrigues, Gupta, and Mendiondo 2014). In this study, the variable monthly flow (VMF) method was used to estimate EFR, which accounts for the intra-annual variability in streamflow by allocating a percentage of the mean monthly flow as EFR for each month (Pastor et al. 2014). As with all EFR methods, there are limitations to the VMF method. For example, it does not consider what was the use of the withdrawn water, or how efficiently it was used. Nor does not account for whether withdrawn water leaves the system or returns (i.e., return flow) and in what state it returns to the system (such as level of contamination). Also, the VMF method does not account for any specific ecological requirements, such as water required for fish populations. Despite these limitations, the VMF method was used because of its ability to capture the seasonal variability of water use within the McKenzie Creek watershed which is important given the agricultural context of the study. The VMF method has also been used for $BW_{available}$ calculations for the Grand River watershed by Kaur et al. (2019, 2023).

The VMF method divides streamflow into three flow types: low, intermediate and high flow. VMF was calculated using Equation (3):

$$VMF = \begin{cases} \text{low flow} = 0.6 * MMF, \text{ if } MMF \leq 40\% MAF \\ \text{intermediate flow} = 0.45 * MMF, \text{ if } 40\% MAF < MMF < 80\% MAF \\ \text{high flow} = 0.3 * MMF, \text{ if } MMF \geq 80\% MAF \end{cases} \quad (3)$$

where MMF is the mean monthly flow and MAF is the mean annual flow.

$BW_{scarcity}$ is evaluated using four classifications as outlined by Hoekstra et al. (2012): low ($BW_{scarcity} < 1$), moderate ($1 \leq BW_{scarcity} < 1.5$), significant ($1.5 \leq BW_{scarcity} < 2$) and severe ($BW_{scarcity} \geq 2$).

To account for increasing water demand due expansion of agricultural land area as well as climate change, two water use scenarios were considered while calculating $BW_{scarcity}$. Scenario 1 (low estimated water use) used observed monthly agricultural water usage as the $BW_{footprint}$ (reported in Wong 2011; Figure 3a). However, since Wong's (2011) agricultural water usage does not differentiate between surface and groundwater extraction the monthly values had to be adjusted. Using the ratio between actual surface water withdrawal ($0.015\,m^3 s^{-1}$) and actual total water withdrawal ($0.059\,m^3 s^{-1}$) (Figure 3c), 25.4% of the monthly agricultural water use was used as the $BW_{footprint}$ for scenario 1. Scenario 2 (high estimated water use) used the 2012 maximum amount of surface water permitted for withdrawal (i.e., $0.298\ m^3 s^{-1}$) as the $BW_{footprint}$ constant (MacVeigh, Zammit, and Ivey 2016; Figure 3c). This scenario represented water withdrawal that may be required to account for warmer climate conditions and increased water demand in the future.

2.3.2 | *GW* Scarcity

GW refers to water from precipitation that does not flow into streams or infiltrates into groundwater but instead remains in the soil for plant growth (Hoekstra et al. 2011).

GW scarcity ($GW_{scarcity}$) was calculated as:

$$GW_{scarcity} = \frac{GW_{footprint}}{GW_{available}} \quad (4)$$

where $GW_{footprint}$ is water that is lost through ET, and $GW_{available}$ is water that is stored in the environment (i.e., soil water content). In the GSFLOW, ET was calculated using the Jensen–Haise method as outlined in Markstrom et al. (2008). Simulated soil water content is estimated for each grid within the watershed and is also saved as the watershed average. Only growing season data from May to October were analysed for the GW scarcity assessment.

3 | Results

3.1 | Land Use Changes

Land use and crop cover types and their changes in the McKenzie Creek watershed between 2011 and 2021 are shown in Figure 2. These changes showed a decreasing trend in forest cover area in the watershed and an increasing trend in the agricultural area. Forest cover area declined at a rate of $1.77\,km^2 year^{-1}$ (or $177\,ha\,year^{-1}$), while agricultural area increased at the rate of 0.55 $km^2 year^{-1}$ (or 55 ha $year^{-1}$) (Figure 2a). This deforestation rate is significant, with the forested area shrinking from 68 km^2 in 2011 to 48 km^2 in 2021, within a 194 km^2 watershed (Figure 2a). Deforestation rates in the Six Nations and non-Six Nations lands were similar (Figure 2b,c). Changes in other land cover types were insignificant. Major crop types within the watershed were cereals (26–40 km^2) and vegetables (36–48 km^2), while the area occupied by all other crop types was < 5 km^2 (Figure 2d, Table 1). Almost two-thirds of the cereal and vegetable crops were grown on the Six Nations lands.

3.2 | *BW* Scarcity

In the McKenzie Creek the primary *BW* usage or withdrawal was for agriculture and dewatering, while water use for livestock and commercial purposes was minimal (Figure 3a). The agricultural *BW* withdrawal occurred between June and September with a maximum withdrawal of $6.73 \times 10^5\,m^3\,month^{-1}$ recorded in July. Dewatering took place throughout the year with about $3 \times 10^5\,m^3$ of water withdrawn each month. Dewatering bodies primarily included pits and quarries. Study results further showed that based on the 2007–2008 data, the daily *BW* withdrawal rate for groundwater (surface water) was 0.044 (0.015), 0.118 (0.000) and 0.008 (0.001) $m^3 s^{-1}$ for agricultural, dewatering and commercial activities, respectively as compared to the respective maximum permitted daily groundwater (surface water) withdrawal rate of 1.436 (0.474), 0.118 (0.000) and 0.008 (0.013) $m^3 s^{-1} day^{-1}$ (Figure 3b,d). Water use data were updated in 2012, and it included two additional water use categories, industrial and miscellaneous. Overall, permitted water withdrawal limits were decreased in 2012, except for surface water withdrawal for dewatering activities which was increased from almost a negligible amount to 5.826 $m^3 s^{-1} day^{-1}$ (Figure 3c). Additionally, in 2012, actual groundwater and surface water withdrawal rates showed a decrease for all categories when compared to the 2007–2008 data with daily *BW* withdrawal rates of 0.038, 0.056 and 0.005 $m^3 s^{-1}$ for agriculture, dewatering and commercial use, respectively (Figure 3e).

The monthly mean rates of simulated $BW_{available}$ and $BW_{scarcity}$ in the McKenzie Creek watershed based on agricultural water usage for both the historical (1961–2020) and future (2021–2100) periods are displayed in Figure 4. During the historical period,

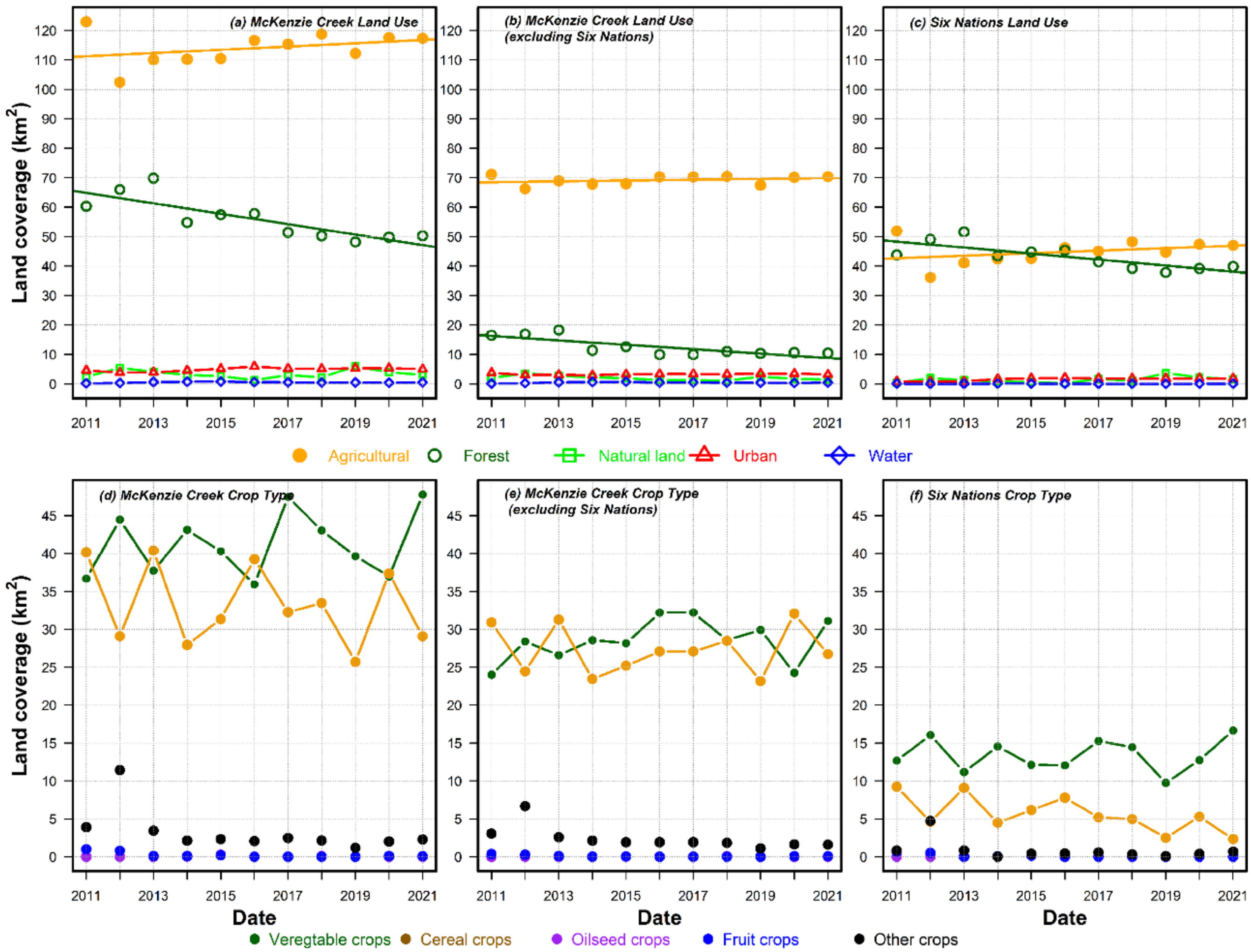

FIGURE 2 | Changes in land use and crop type from 2011 to 2021. (a) Land use for the entire McKenzie Creek watershed, (b) land use for the McKenzie Creek watershed (excluding Six Nations area), (c) land use in only the Six Nations portion of the McKenzie Creek. (d) Crop type for the entire McKenzie Creek watershed, (e) crop type for the McKenzie Creek watershed (excluding the Six Nations area) and (f) crop type in only the Six Nations portion of McKenzie Creek. Data adapted from Agriculture and Agri-Food Canada (2023).

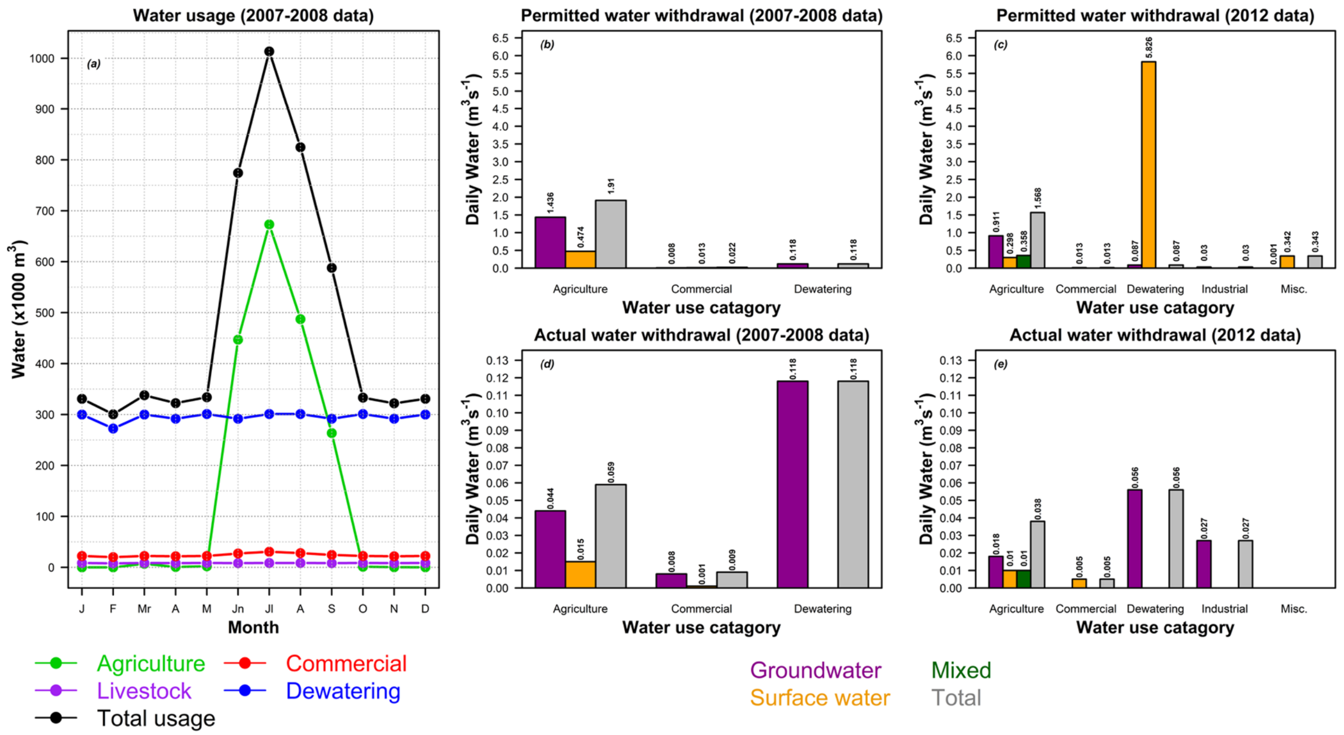

FIGURE 3 | McKenzie Creek water usage. (a) Monthly water use for agriculture (light green), commercial activities (red), livestock (purple), dewatering (blue) and total usage (black). (b, c) Permitted water withdrawal and (c, d) actual water withdrawal from the groundwater (purple), surface water (yellow), mixed (referring to both surface and groundwater; green) and total (grey) sources for five main water use categories: agriculture, commercial, dewatering, industrial and miscellaneous. Adapted from Wong (2011) for 2007–208 data MacVeigh, Zammit, and Ivey (2016) for 2012 data.

the $BW_{available}$ rate ranged from 0.35 to 3.52 m^3 s^{-1} for control simulations (Figure 4a) and from 0.39 to 3.81 m^3 s^{-1} for the multimodel average of historic simulations under both RCP 4.5 and 8.5 scenarios (Figure 4b,c; shaded areas represent a multimodel range). $BW_{available}$ peaked in March and was lowest in August. Results for the past $BW_{scarcity}$ (scenario 1) showed that water scarcity was near zero from January to April and November to December for both control and historic simulations. Between May and September, $BW_{scarcity}$ ranged from 0.11 in September to 0.22 in July for control simulations, and from 0.10 in September to 0.21 in July under RCP 4.5 and 0.22 in July under RCP 8.5 for historic simulations. In contrast, $BW_{scarcity}$ occurred throughout the year under scenario 2, which used the maximum permitted surface water withdrawal of 0.298 m^3 s^{-1}. *BW* scarcity levels (scenario 2) ranged from 0.10 in March to 1.26 in September for control simulations, and from 0.11 in March to 1.18 in September under both RCP 4.5 and RCP 8.5 for historic simulations.

Furthermore, future monthly average $BW_{available}$ is projected to range from 0.39 to 3.94 m^3 s^{-1} for RCP 4.5 and from 0.40 to 3.80 m^3 s^{-1}for RCP 8.5 across the three periods (2020s, 2050s and 2090s) (Figure 4b,c). $BW_{available}$ is expected to be most limited in July and August and highest in March (Figure 4b,c). Additionally, while $BW_{available}$ is projected to increase in winter (December, January and February) and decrease in March and November (RCP 8.5 only), it is expected to change very little during the growing season (May to October) across all three future periods. Regarding projected water scarcity, during the growing season under scenario 1, $BW_{scarcity}$ is projected to range from near zero in May for both RCP 4.5 and 8.5, to 0.23 (RCP 4.5) and 0.2 (RCP 8.5) in July (Figure 4e,f). There is no change in $BW_{scarcity}$ between the three future periods under RCP 4.5, where only a slight increase is projected to occur in water scarcity in June and August under RCP 8.5. Projections of $BW_{scarcity}$ under scenario 2 during the growing season range from 0.49 in May to 1.18 in August under RCP 4.5. Under RCP 8.5, $BW_{scarcity}$ is projected to range from 0.53 in May to 1.20 in September. The largest increase in $BW_{scarcity}$ during the 21st century is projected to occur in September (RCP 4.5) and August (RCP 8.5), while October is projected to experience the biggest decrease during the growing season.

Statistical analysis of monthly $BW_{scarcity}$ using Mann–Kendall and Sen's Slope techniques for the May to October period showed minimal changes in water scarcity across the three main future periods (2020s, 2050s and 2090s) and the long-term average (2021–2099) (Table 2). Additionally, the number of months each year with $BW_{scarcity}$ (scenario 2 water usage) classified as 'moderate', 'significant' or 'severe' did not change over the study period. The average frequency of months when $BW_{scarcity}$ was equal to or greater than 1.0 ranged from 2.4 to 2.5 months per year for both control and RCP 4.5 and 8.5 scenarios (Figure 5a). The average number of months when $BW_{scarcity}$ was equal to or greater than 2.5 ranged from 1.1 to 1.2 months per year (Figure 5b), and it was 0.5 months per year when $BW_{scarcity}$ was equal to or greater than 3.0 (Figure 5c).

3.3 | *GW* Scarcity

Figure 6a,b shows the growing season $GW_{footprint}$ (ET) and $GW_{available}$ (soil water content). During the historical period

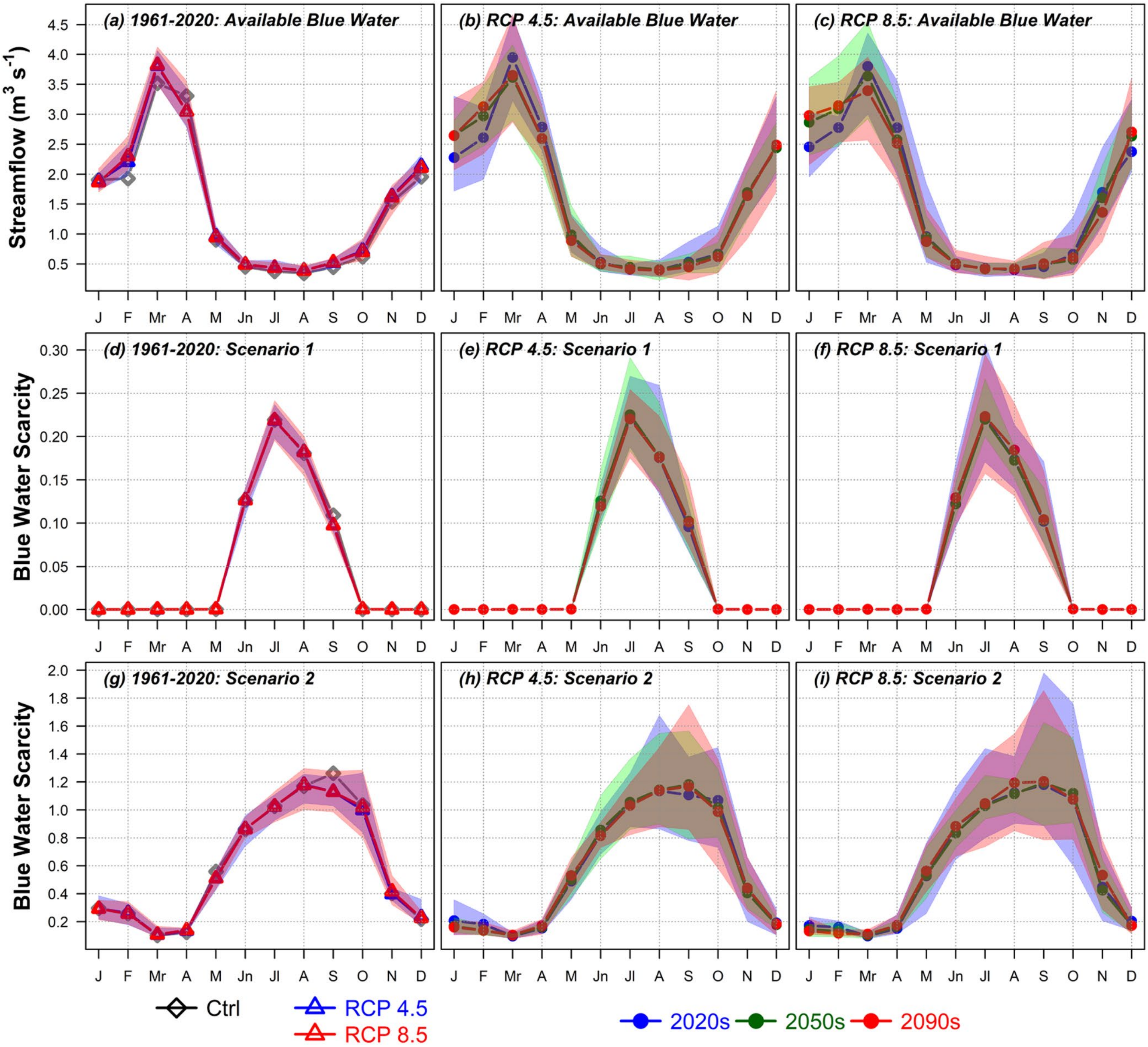

FIGURE 4 | Mean of monthly available Blue Water ($BW_{available}$) and Blue Water scarcity ($BW_{scarcity}$; based on agricultural surface water usage) for the McKenzie Creek. $BW_{available}$ (a–c) was calculated using the variable monthly flow (VMF) method, $BW_{scarcity}$ was calculated using low estimated water use (scenario 1; d–f) and high estimated water use (scenario 2; h–j). The first column represents data from 1961 to 2020 where Ctrl is control data, the second column is projections under RCP 4.5 and the third column is projections under RCP 8.5. Future RCP projections are split into three periods: 2020s (2021–2039), 2050s (2040–2069) and 2090s (2070–2099). Multimodel range is represented by the shaded area.

(1961–2020), multimodel average of $GW_{footprint}$ during the growing season increased at a rate of 0.96 mm year^{-1} for control simulations and 0.35 mm year^{-1} (RCP 4.5) and 0.4 mm year^{-1} (RCP 8.5) for historic simulations. Over the same period, control $GW_{available}$ increased at a rate of 2.16 mm year^{-1}, while $GW_{available}$ decreased at a rate of 5.60 mm year^{-1} (RCP 4.5) and 6.16 mm year^{-1} (RCP 8.5). The rate of change of $GW_{scarcity}$ between 1961 and 2020 was near zero for both control and historic simulations. During this period, $GW_{scarcity}$ was 0.30 for control simulations and 0.33 for historic simulations (Figure 6c). Future projects (2021 to 2099) showed that the multimodel average of annual ET increased at a rate of 0.10 (0.28) mm year^{-1} under RCP 4.5 (RCP 8.5), and future soil moisture content decreased at a rate of 3.35 (6.51) m year^{-1} under RCP 4.5 (RCP 8.5). Projected $GW_{scarcity}$ (Figure 6c) is expected to increase from 2021 to 2099 at annual rates of 0.11 (0.28) under RCP 4.5 (RCP 8.5) due to enhanced ET caused by warmer temperatures and influenced by soil characteristics.

Seasonal total ET and soil water content are shown in Figure 6d–i, respectively. During the 1961–2020 growing season, control ET ranged from 31.2 to 89.4 mm year^{-1}, while historic simulations ranged from 32.0 to 90.5 (RCP 4.5) and 91.2 mm year^{-1} (RCP 8.5). Soil water content ranged from 135.3 to 634.2 mm year^{-1} for the control simulation, and from 130.6 to 595.4 (RCP 4.5) and 589.8 mm year^{-1} (RCP 8.5). Past $GW_{scarcity}$ ranged from 0.06 to 0.52 for control simulations and from 0.07 to 0.57 for both RCP simulations. $GW_{footprint}$, $GW_{available}$ and $GW_{scarcity}$ were highest

TABLE 2 | Results of Mann–Kendall and Sen's Slope statistics tests for monthly mean Blue Water scarcity ($BW_{scarcity}$) between May and October; Mann–Kendall *S* followed by Sen's slope statistics in brackets.

Climate scenario	Water use scenario	2020s (2021–2039)	2050s (2040–2069)	2090s (2070–2099)	Long term (2021–2099)
RCP 4.5	Scenario 1	−6.00e + 1 (−3.51e − 7)	−7.80e + 1 (−1.18e − 7)	−2.91e + 2 (−4.33e − 7)	5.20e + 1 (3.87e − 9)
	Scenario 2	1.36e + 2 (0.00)	0.00 (−2.54e − 9)	−8.45e + 2 (0.00)	−9.32e + 2 (−2.582 − 5)
RCP 8.5	Scenario 1	−2.40e + 1 (−1.30e − 7)	1.32e + 2 (1.72e − 7)	−5.89e + 2 (−1.08e − 6)	1.08e + 3 (9.74e − 8)
	Scenario 2	1.06e + 2 (0.00)	7.38e + 2 (0.00)	−1.35e + 3 (0.00)	1.96e + 3 (5.97e − 5)

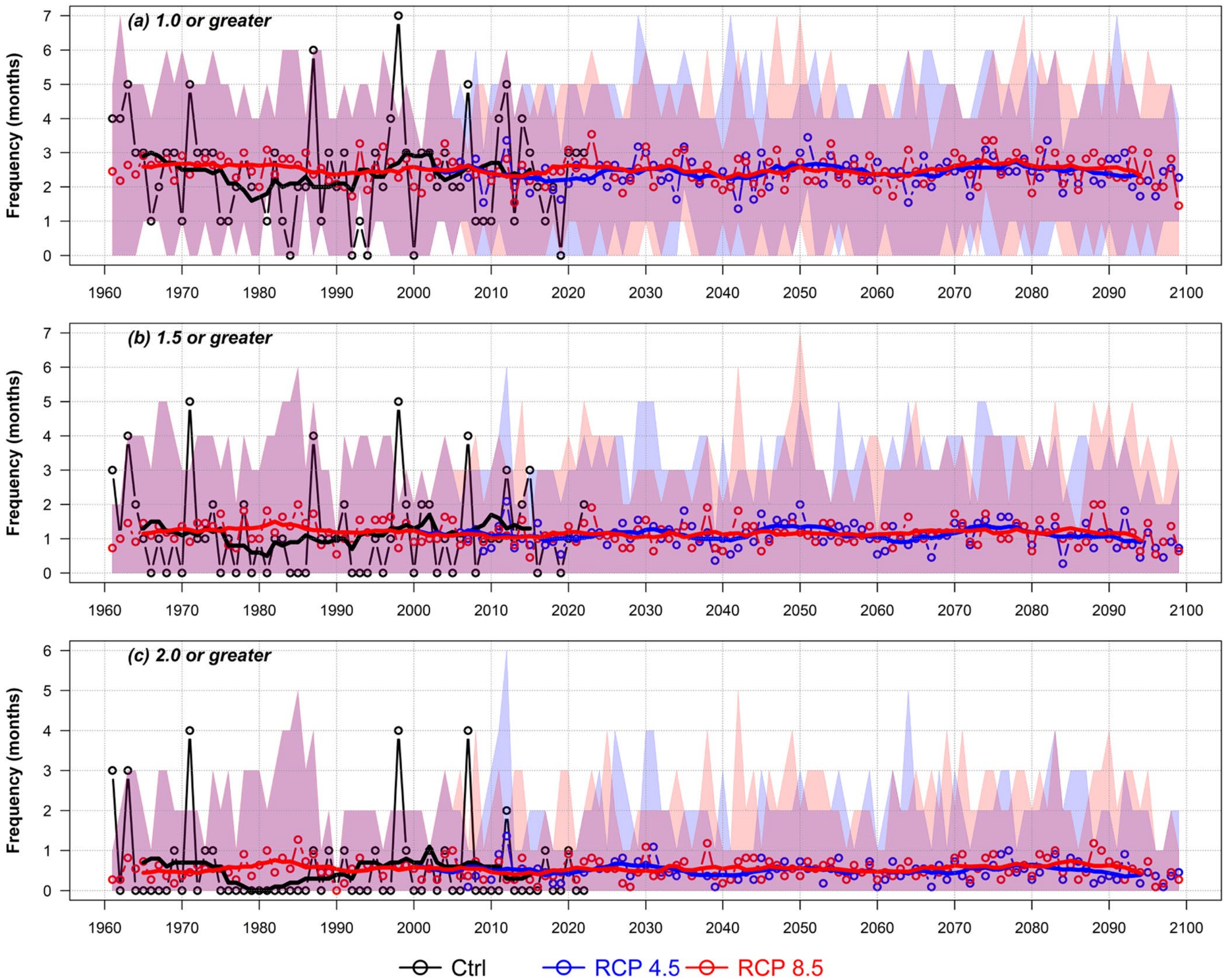

FIGURE 5 | Number of months each year where Blue Water scarcity ($BW_{scarcity}$ under scenario 2) is equal to or above (a) 1.0 (*moderate scarcity*), (b) 1.5 (*significant scarcity*) and (c) 2.0 (*severe scarcity*). Ctrl is the control data, and thick solid lines are 10-year moving averages. Multimodel range is represented by the shaded area.

in May and lowest in October. ET under RCP 4.5 and 8.5 is projected to increase relative to the 1961–2020 average. However, RCP 4.5 ET will change very little over the 21st century, while RCP 8.5 shows a more progressive increase throughout the century (Figure 6d–f). Similar trends were observed for monthly total soil water content, with an overall decrease relative to the

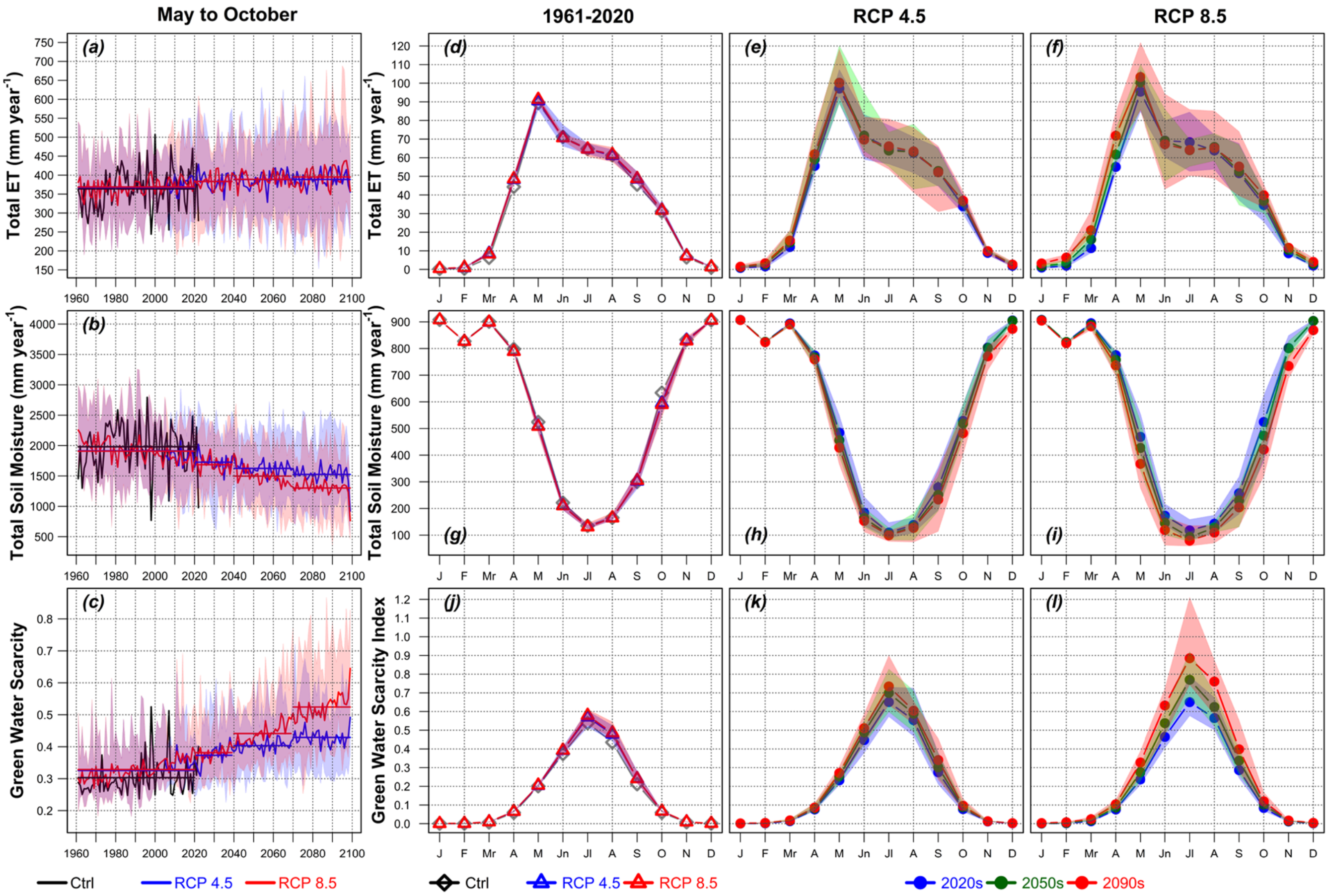

FIGURE 6 | Green water footprint ($GW_{footprint}$; evapotranspiration, ET) (top row), green water availability ($GW_{available}$; soil water content) (middle row) and $GW_{scarcity}$ (bottom row). (a–c) Annual total ET and soil water content, and annual average $GW_{scarcity}$ from May to October. Monthly total ET for (d) 1961–2020, (e) RCP 4.5 and (f) RCP 8.5. Monthly total soil water content for (g) 1961–2020, (h) RCP 4.5 and (i) RCP 8.5. Monthly average $GW_{scarcity}$ data for (j) 1961–2020, (k) RCP 4.5 and (l) RCP 8.5. Future RCP projections are divided into three long-term periods: 2020s (2021–2039), 2050s (2040–2069) and 2090s (2070–2099). The multimodel range is represented by shaded areas.

1961–2020 average. Only RCP 8.5 soil water content showed a progressive decline throughout the 21st century (Figure 6g–i).

As a result of these changes in $GW_{footprint}$ and $GW_{available}$, $GW_{scarcity}$ was projected to increase from 0.37 (RCP 4.5) and 0.38 (RCP 8.5) in the 2020s to 0.40 (RCP 4.5) and 0.44 (RCP 8.5) in the 2050s, and to 0.43 (RCP 4.5) and 0.52 (RCP 8.5) in the 2090s (Figure 6c). Seasonally, $GW_{scarcity}$ during the growing season will increase throughout the 21st century, peaking in July at 0.73 (RCP 4.5) and 0.89 (RCP 8.5) by the 2090s (Figure 6j–l).

The spatial distribution of $GW_{scarcity}$ revealed a contrast between the Norfolk Sand Plains (western portion of the watershed) and the Haldimand Clay Plains (central and eastern portions) (Figure 7). $GW_{scarcity}$, calculated relative to the baseline period (1961–2020), is projected to increase the most in the Norfolk Plains, with water scarcity in some grids reaching between 2.0–2.5 (RCP 4.5) and 2.5–3.0 (RCP 8.5). In contrast, water scarcity in the Haldimand Clay section ranged from 0 to 0.3 during the baseline period for most grids and is projected to increase very little throughout the 21st century. Temporally, most grids are not expected to experience a change in $GW_{scarcity}$ between the 2020s, 2050s, and 2090s, except for the 2090s under RCP 8.5, where several HRUs in the western portion of the watershed are projected to see an increase in $GW_{scarcity}$. The spatial distribution of ET and soil water content can be found in Figures S2 and S3.

4 | Discussion

Climate warming is expected to make this part of the Great Lakes region warmer and wetter with more heatwaves and more frequent and intense extreme rain events (Deen et al. 2021; McDermid, Fera, and Hogg 2015; Wazneh, Arain, and Coulibaly 2019; Zhang et al. 2020). At the same time longer and more pronounced dry periods are also projected to occur (Deen et al. 2021). Consequently, McKenzie Creek streamflow is projected to increase in winter (December, January and February) due to earlier snowmelt and increased seasonal rainfall. Spring (March, April and May) streamflow is projected to decrease because of lower snowmelt, while summer (June, July and August) streamflow is expected to experience little to no change (Deen et al. 2023). These changes in climate and hydrology patterns will affect *BW* and *GW* scarcity in the McKenzie Creek watershed in the future.

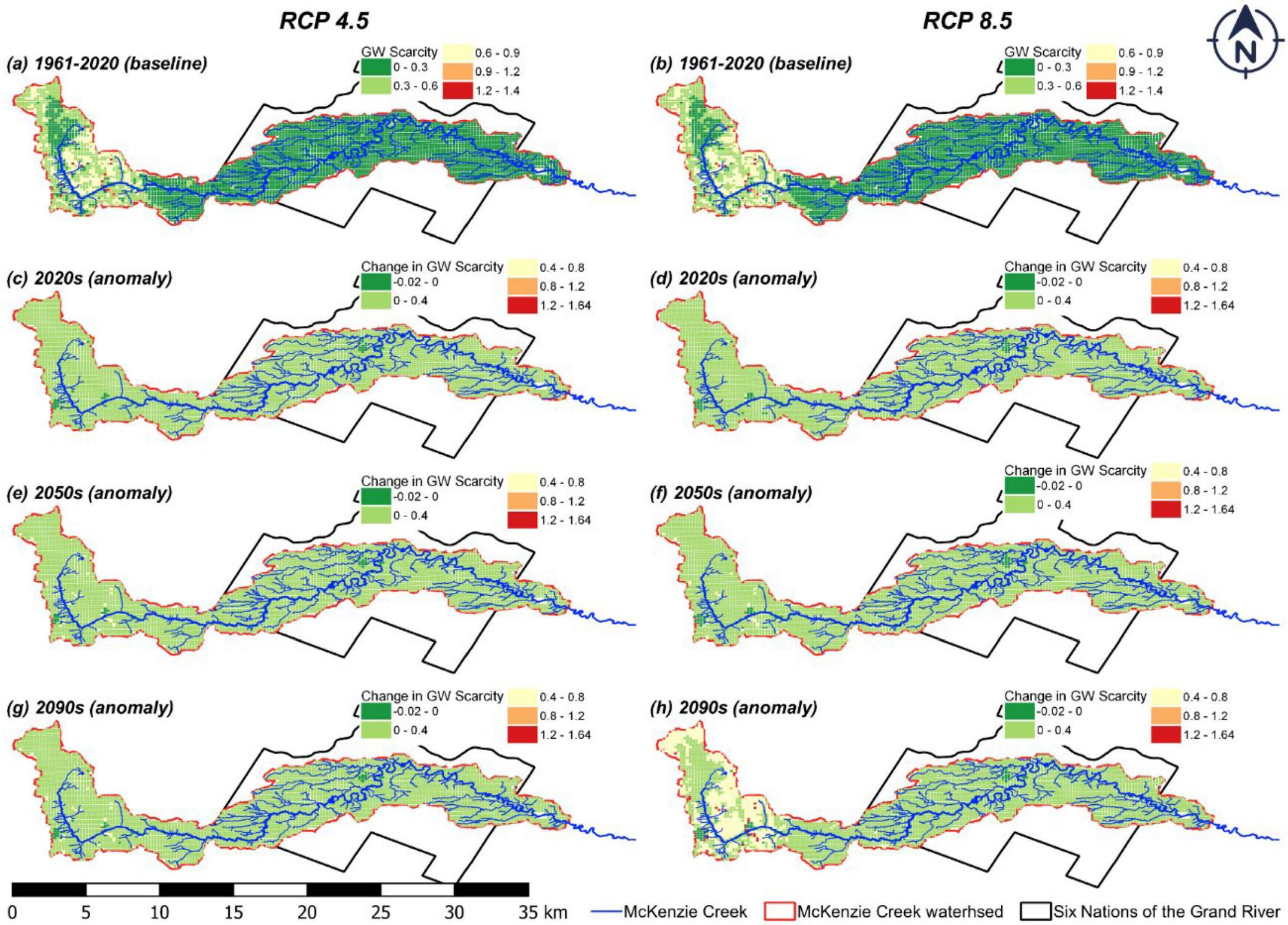

FIGURE 7 | Change in monthly mean green water scarcity ($GW_{scarcity}$) during the growing season (May to October) relative to baseline average. (a, b) Baseline $GW_{scarcity}$ (1961–2020), (c, d) 2020s (2021–2039), 2050s (2040–2069) and 2090s (2070–2099) under RCP 4.5 (left column) and 8.5 (right column).

4.1 | Blue Water

4.1.1 | Water Use and *BW* Scarcity

$BW_{available}$ within the McKenzie Creek watershed during the growing season is projected to experience little or no change over the 21st century (Figure 4a–c). Therefore, if McKenzie Creek water users continue with the current monthly surface water withdrawal (scenario 1, or 25.4% of total monthly agricultural water use), $BW_{scarcity}$ will remain 'low' according to Hoekstra et al. (2012) classification. This indicates that the current $BW_{footprint}$ (surface water withdrawal) will not exceed available *BW*. As a result, McKenzie Creek streamflow will not be negatively impacted by agricultural activities if monthly surface water extraction continues at the rate reported by Wong (2011). These findings align with Kaur et al. (2023), who also reported 'low' projected $BW_{scarcity}$ for the southern portion of the Grand River watershed in their study. Historically, $BW_{scarcity}$ has been 'low' between May and October in the Great Lakes-St. Lawrence Basin (Hoekstra et al. 2012).

However, scenario 1 water use trends are unlikely to continue in the future under warmer climate and land use changes. Agricultural data from 2000 to 2015 in the Grand River watershed showed an increasing trend in field crops (grain, soybean and winter wheat) and certain horticulture crops (sweet corn and tomato) areas (McNeill 2018). Furthermore, satellite data from Agriculture and Agri-Food Canada (2023) showed that agricultural land coverage in the McKenzie Creek watershed increased at a rate of $0.55\,km^2 year^{-1}$ (or $55\,ha\,year^{-1}$) between 2011 and 2021 (Figure 2). These trends, along with rising temperatures and declining summer precipitation as outlined in Deen et al. (2021), suggest that *BW* withdrawal has increased since Wong (2011) and MacVeigh, Zammit, and Ivey (2016) water usage reports and will likely continue to increase over the next century.

Additionally, neither water use report includes water withdrawal within the Six Nations territory. This means that scenario 1 water usage underestimates $BW_{scarcity}$ in the McKenzie Creek watershed. Agricultural land in the McKenzie Creek watershed (excluding the Six Nations area), where GRCA reported water use, is approximately 1.5 times larger than agricultural land in the Six Nations portion of the watershed (Figure 2b,c). Crop types between the two areas are similar, with vegetable and cereal crops being the dominant types (Figure 2e,f). Therefore, a significant amount of water from Six Nations are unaccounted for, making scenario 2 water usage (constant withdrawal of $0.298\,m^3 s^{-1}$) a useful alternative to the observed $BW_{footprint}$.

Under this estimated water use scenario, $BW_{scarcity}$ is projected to become 'moderate' during the growing season. This level of water scarcity suggests that McKenzie Creek streamflow will be altered by water withdrawal and may not be able to sustainably support the environmental flow requirements (EFRs) of the watershed. Such changes in water resource availability will negatively impact the overall ecological health of the watershed. This is particularly concerning given the existing water pollution challenges in McKenzie Creek. Water quality data collected between April 2019 and November 2019 showed high levels of contamination, with turbidity, total suspended solids, total phosphorus and total nitrogen samples exceeding provincial guidelines in the Six Nations portion of the watershed and two nearby sites (Makhdoom 2021). Increased *BW* withdrawal for irrigation could lead to more agricultural runoff, further degrading water quality.

To mitigate ecological damage, the GRCA can adjust the maximum permitted surface water withdrawal levels for agricultural and other activities and should proactively monitor water resource consumption and climatic conditions to take timely remedial actions.

4.1.2 | Climate Change and *BW* Scarcity

A major concern with warming climate conditions is that climate change-related streamflow fluctuations and competing water demands will reduce water availability and supply in Southern Ontario (Andrey, Kertland, and Warren 2014). However, while $BW_{scarcity}$ does increase between the moderate (scenario 1) and high (scenario 2) water use scenarios, the effects of climate warming in the McKenzie Creek watershed, such as increased temperature and greater variability in precipitation (Deen et al. 2021; Deen et al. 2023), do not appear to affect $BW_{scarcity}$ between the three future periods (2020s, 2050s and 2090s). Additionally, there is very little difference in the projected $BW_{scarcity}$ between the future climate scenarios (RCP 4.5 and RCP 8.5).

Similar observations have been made by Kaur et al. (2023) in the southern portion of the Grand River watershed. The lack of changes between future periods and climate scenarios is due to the projected McKenzie Creek streamflow, which shows little to no change from late spring to early fall (Deen et al. 2023). Low changes in future streamflow during these months were also found in the Grand River and surrounding watersheds (Champagne et al. 2020; Li et al. 2016).

4.2 | Green Water

4.2.1 | Increasing *GW* Scarcity

Unlike *BW*, *GW* is more affected by climate warming. During the growing season, $GW_{footprint}$ (ET; Figure 6a,e,f) is projected to slightly increase, while $GW_{available}$ (soil water content; Figure 6b,h,i) is expected to decrease. Soil dryness will occur faster than an increase in ET, suggesting that soil water retention, rather than atmospheric water loss, is the dominant factor for $GW_{scarcity}$ in the watershed. This may be due to soil characteristics (discussed further in 4.2.2) and projected lower precipitation during the growing season (Deen et al. 2023).

$GW_{scarcity}$ is projected to increase until 2099, with the 30-year mean reaching 43% scarcity in the 2090s under RCP 4.5 and 52% scarcity under RCP 8.5 (Figure 6c). This indicates that under high warming conditions, nearly half of *GW* resources will be lost through ET or reduced precipitation, compared to the historical period (1961–2020) when it was just a third. These projections are similar to future $GW_{scarcity}$ predictions by Kaur et al. (2023) for southern Grand River watersheds and Standardised Precipitation Evapotranspiration Index (SPEI) summer drought projections for nearby Guelph region by Tam et al. (2019).

Climate change is expected to alter the growing season in Southern Ontario. Warmer temperatures will lengthen the growing season and increase available heating units, benefiting agricultural production (Climate Risk Institute 2023). Within the McKenzie Creek watershed, the growing season occurs between May and October (Wong 2011). If warmer temperatures allow crops to be planted earlier, farmers may benefit from higher levels of $GW_{available}$ (soil water content) in April (Figure 6h,i) to offset declining levels during the regular growing season. An earlier start to the growing season may reduce $GW_{scarcity}$ within the watershed, as the increase in soil water content between May and April would be greater than the expected water loss through ET between May and April (Figure 6e,f). This could result in better agricultural yields contributing to regional food security. However, more research on the McKenzie Creek watershed's crops, growing requirements and water demand is needed to determine if this is a viable adaptive solution to climate change.

It should be noted that $GW_{scarcity}$ could be higher depending on the method used to calculate ET in the GSFLOW model, which allows for several different methods. For this study, we explored three ET calculation methods: (1) a modified version of Jensen–Haise's formulation, (2) Hamon's formulation and (3) the Hargreaves–Samani formulation (see Markstrom et al. 2008 for details). Ultimately, ET derived from the Jensen–Haise method was used for calculating $GW_{scarcity}$ because it provided simulated ET values similar to those observed in forest and crop ecosystems at Turkey Point Environmental Observatory (TPEO) (Arango Ruda and Arain 2024). The average annual ET at TPEO in a deciduous forest was 367 mm from 2012 to 2020, while the average ET simulated by GSFLOW using observed climate data over the same period was 370 mm. Additionally, Eichelmann et al. (2016) found that the average growing season (May to October) ET for corn and switchgrass at Seaforth and Elora, Southern Ontario, was approximately 410 mm and 478 mm, respectively. However, the Hargreaves–Samani method overestimated simulated ET by approximately 100–150 mm $year^{-1}$ compared to Jensen–Haise's ET, while Hamon's formulations underestimated ET by about 100 mm $year^{-1}$ compared to Jensen–Haise's formulation. Higher ET would further increase $GW_{scarcity}$ than reported in this study. More work is needed to determine which approximation method is best suited for the McKenzie Creek watershed.

Additionally, since GSFLOW was validated using streamflow, there are uncertainties in $GW_{scarcity}$ as it relies on soil water content which was not validated due to a lack of observed data. This highlights the need for more observational studies in dominant crop types such as corn, soybeans, sweet potato, wheat and others, as well as soil water surveys in the Great Lakes region.

4.2.2 | Spatial Dimension of *GW* Scarcity

As previously mentioned, $GW_{scarcity}$ is more influenced by soil water retention than atmospheric loss in the watershed, highlighting the importance of soil characteristics in McKenzie Creek's *GW* scarcity. Figure 7 shows a clear divide in the watershed based on differences in soil composition and permeability (Figure 1d,e). The eastern portion of the watershed (Norfolk Sand Plains) consists of sand, gravel, diamicton and organic deposits (MacVeigh, Zammit, and Ivey 2016). Soil permeability in this region is high, resulting in less water retention in the soil (i.e., $GW_{available}$). Conversely, the Haldimand Clay portion of the watershed (central and eastern region) consists mainly of clay and silt with sections of sand throughout the McKenzie Creek watercourse, resulting in less water drainage and higher soil water content. ET throughout the watershed is spatially uniform due to similar meteorological controls.

Our study results on the spatial variability of $GW_{scarcity}$ highlight potential challenges for water resource utilisation among Indigenous (i.e., the Six Nations area) and non-Indigenous communities in the watershed. Farms in the western, non-Six Nations section of the watershed (i.e., Brant County) have the highest density of field crop production in the entire Grand River (McNeill 2018), and agriculture in the sand plains is described as 'intensive' (MacVeigh, Zammit, and Ivey 2016). Lower available *GW* during the growing season may lead to increased *BW* (surface or groundwater) withdrawal (i.e., *BW* footprint) in upper non-Indigenous sections of McKenzie Creek, causing reduction of available water (i.e., *BW*) downstream for the Six Nations area.

5 | Conclusion

This study analysed *BW* and *GW* scarcity in the McKenzie Creek watershed in Ontario, Canada, under two climate warming scenarios: RCPs 4.5 (moderate warming) and 8.5 (high warming). Despite its small size, the McKenzie Creek watershed is a crucial provider of ecosystem services for agriculture and other activities in the region. This is the first study to quantify water scarcity in a Great Lakes region and the McKenzie Creek watershed at a high spatial resolution ($200\times200\,m^2$).

The results indicated that $BW_{scarcity}$ during the growing season (May to October) will remain low under scenario 1 (25.4% of total monthly agricultural water use). Satellite data showed an increase in agricultural land in the watershed, suggesting that total water withdrawal has likely increased and will continue to do so. Therefore, the maximum permitted water withdrawal rate ($0.298\,m^3\,s^{-1}$) under scenario 2 provided a more realistic estimate of future water use. Under this scenario, $BW_{scarcity}$ would rise moderately. These findings suggest that future maximum permitted water withdrawals could harm the watershed's ecology and degrade water quality due to agricultural runoff. However, due to limitations in available water use data for Six Nations, these $BW_{scarcity}$ predictions are likely underestimations. Additionally, $BW_{scarcity}$ will vary based on the method used to calculate EFRs. Future research should explore alternative EFR calculation methods that better reflect the watershed's ecological needs.

Annual and monthly $GW_{scarcity}$ was projected to progressively increase throughout the century. The effects of increased $GW_{scarcity}$ may be mitigated by an earlier start to the growing season. Farmers might benefit from higher soil water content and warmer conditions, but more research is needed to determine if this is an adequate adaptive solution to soil drying in the watershed. Spatially, the western portion of the watershed is projected to experience higher water scarcity due to lower soil water retention. $GW_{scarcity}$ during the growing season may lead to increased *BW* withdrawal in the western portion, reducing available water resources downstream for the Six Nations. However, more research is needed into the water use and specific crop varieties being planted in the watershed to better understand the capacity of farmers in both communities to adapt to increasing water demand and decreasing water availability in changing climate.

This study provides water resource managers and regional planners with crucial insights into potential challenges in the watershed due to increased water use under changing climate conditions. It can also serve as a template for assessing water scarcity in other Great Lakes region watersheds. The study underscores the urgent need for a comprehensive survey of water usage in the McKenzie Creek watershed, including the Six Nations of the Grand River reserve. Such a survey would be instrumental in fully understanding the extent of *BW* scarcity in McKenzie Creek, allowing for more effective and equitable water management strategies.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.