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► **To cite this version:**

Charlotte Poirier, Guillaume Fortin, Vincent Dubreuil. Spatial and temporal characteristics of past droughts in New Brunswick (1971–2020). *International Journal of Climatology*, 2023, 43 (15), pp.7183-7198. 10.1002/joc.8259 . halshs-04430831

HAL Id: halshs-04430831

<https://shs.hal.science/halshs-04430831>

Submitted on 22 Feb 2024

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Spatial and temporal characteristics of past droughts in New Brunswick (1971–2020)

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Abstract

This study aimed to provide a historical picture from 1971 to 2020 of the state of droughts in New Brunswick (NB). More specifically, we wished to determine whether there were statistically significant trends using two drought indices: the Standardized Precipitation Index (SPI) and the Standardized Precipitation-Evapotranspiration Index (SPEI). Monthly precipitation (rain and snow) and average maximum and minimum temperatures were obtained from 10 stations located in New Brunswick. Then, we applied Mann–Kendall and Sen's Slope's nonparametric tests to these two indices at a 1-, 3-, 6- and 12-month timescale. The results have shown that the average value for the SPI and SPEI evolution throughout the study period indicated a decrease in indices values (at 95% confidence level). The temporal evolution of the SPI and SPEI were similar at various timescales regarding severities and intensities. However, there were still slight differences in the fluctuation values, especially during the last 20 years of the study period. At a 12-month timescale, both indices indicated the driest years as being 2020, 2001 and 2004. The SPEI Miramichi, Saint John and Moncton stations had maximum negative MK values (−0.259, −0.221 and −0.215), respectively. As for spatial distribution, four stations located in the south stood out with the highest increase in dry conditions and significantly negative trends (meaning increased drought in this case). Stations in the northern part of the province (Bathurst and Charlo) show non-significant trends. This study suggests a slight drought increase trend exists in New Brunswick, while an increase in annual precipitation is expected between 42 and 324 mm by 2100 according to climate scenario RCP8.5 of CMIP6.

KEYWORDS

drought, New Brunswick, Standardized Precipitation Evaporation Index (SPEI), Standardized Precipitation Index (SPI), trend analysis

1 | INTRODUCTION

Despite their many induced effects, droughts are too often underestimated in climate change adaptation. Even

if the exposure of some areas to droughts is low, such as for the Maritime provinces in Canada, the vulnerability factors can remain present. As witnessed in the summer of 2020, the province of New Brunswick recently

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experienced atypical dry conditions. Adding the fact that there is little literature on the historical portrait of droughts in eastern Canada and even fewer targeting the province of New Brunswick, a need for information was identified. The summer of 2020 was atypical, with exceptionally dry conditions for the province of New Brunswick. Indeed, according to Agriculture and Agri-Food Canada's drought monitoring tool (Agriculture and Agri-Food Canada, 2021), some areas of New Brunswick have experienced their first extreme drought event since at least 2002. The summer of 2001 also had a drought event of notable importance, affecting all of Canada, including the Atlantic provinces (Wheaton et al., 2008). As stated in the Canada Changing Climate Report (CCCR) (Environment and Climate Change Canada, 2019), changes in climate conditions are already apparent. Historically, the country's average annual temperatures have increased by 1.7°C in 68 years (ECCC, 2019). Canada's average yearly rainfall increases precipitation, including in the Atlantic region (Zhang et al., 2018). However, this increase is more frequent in winter as a decrease in summer precipitation is expected for southern Canada. Still, considering these precipitation trends, global-scale studies have shown how higher temperatures can translate to increased evaporation and dryer land conditions favourable to drought-like needs (Gobena & Gan, 2013). Moreover, as noted in the most recent IPCC reports (e.g., Masson-Delmotte et al., 2021), extreme events, including heatwaves and droughts, have increased in recent decades in North America and across the globe because of human influence. On the other hand, droughts in eastern Canada are less well documented than in western Canada, where major drought episodes hit the area regularly (Bonsal et al., 2020; Tam et al., 2018).

When looking at the specific hydroclimatological risks of droughts, the vulnerability factors remain present even if the exposure for the Maritime provinces is relatively low compared to the rest of Canada. The scarcity of droughts tends to increase Maritime communities' vulnerability and lack of preparedness as they often do not have adequate adaptive capacity when a drought occurs (Bonsal et al., 2011). This climate surprise is frequent elsewhere globally, Dubreuil (1997) reported. Indeed, the vulnerability of western France to drought has been demonstrated. It is a temperate region that is humid in summer, located on the edge of the Atlantic Ocean and not very conducive to drought. The geographical situation of this region thus presents certain similarities with our study area. For New Brunswick, major economic sectors, such as agriculture, which represented 619\$ million in gross farm income in 2016, can be threatened by droughts with many direct and indirect impacts

on productivity levels (Government of New Brunswick, 2017). The forest industry is the most significant economic sector in the province, generating a total revenue of \$838 million in 2017 (Government of New Brunswick, 2010a). The numerous wildfires that occurred in Canada in the summer of 2023, particularly in Eastern Canada (Quebec, Nova Scotia, the Southwest of New Brunswick), are attributable to global warming caused by human activities and directly linked to water deficits (Barnes et al., 2023). The socio-economic (closure of schools and businesses, evacuation of populations, mental distress and physical health problems and so on) and environmental impacts (loss of habitat, water contamination, etc.) of these fires are dramatic for the communities affected and require intervention plans. One of the critical variables in fire management is the degree of humidity, which is closely linked to dry spells. NB forests are potentially at risk from such fires, adding another reason to better understand and quantify drought and fire-prone conditions in the province. The infestation of pest insects, the appearance of new diseases, more favourable conditions for forest fires, the slowing down in regeneration of certain tree species, and the shifting of the distribution of different forests to the north have all had considerable effects on the forestry sector and can be related to droughts (World Wildlife Fund Canada, 2017).

Furthermore, we cannot forget the direct impact of droughts on clean water stream levels and temperature, which are essential to some of New Brunswick's population for daily consumption (groundwater recharge and well levels) and the proper functioning of habitats and ecosystems. The study of droughts in the province of New Brunswick is particularly important for improving water resource management in the context of global warming. For example, according to Statistics Canada's census, the Greater Moncton area has been the fastest-growing urban area in Canada since 2016, with a growth rate of 5.3% in 2022). This increase in population translates directly into a rise in demand for water from municipal drinking water supplies. Municipalities have to ensure that they have sufficient quantities of water even when hit by drought. The province has identified drought as a priority hydroclimatic risk in its latest climate change adaptation plan (Government of New Brunswick, 2022). We conducted this study to provide the province's decision-makers with quantitative data on drought.

Despite their many induced effects, droughts are too often underestimated in climate change adaptation. These hydroclimatic spatiotemporal characteristics are sometimes challenging to determine (Beran & Rodier, 1985). A drought event can affect a large area, and its duration can spread up to several months, making the identification of the formation and dissipation time

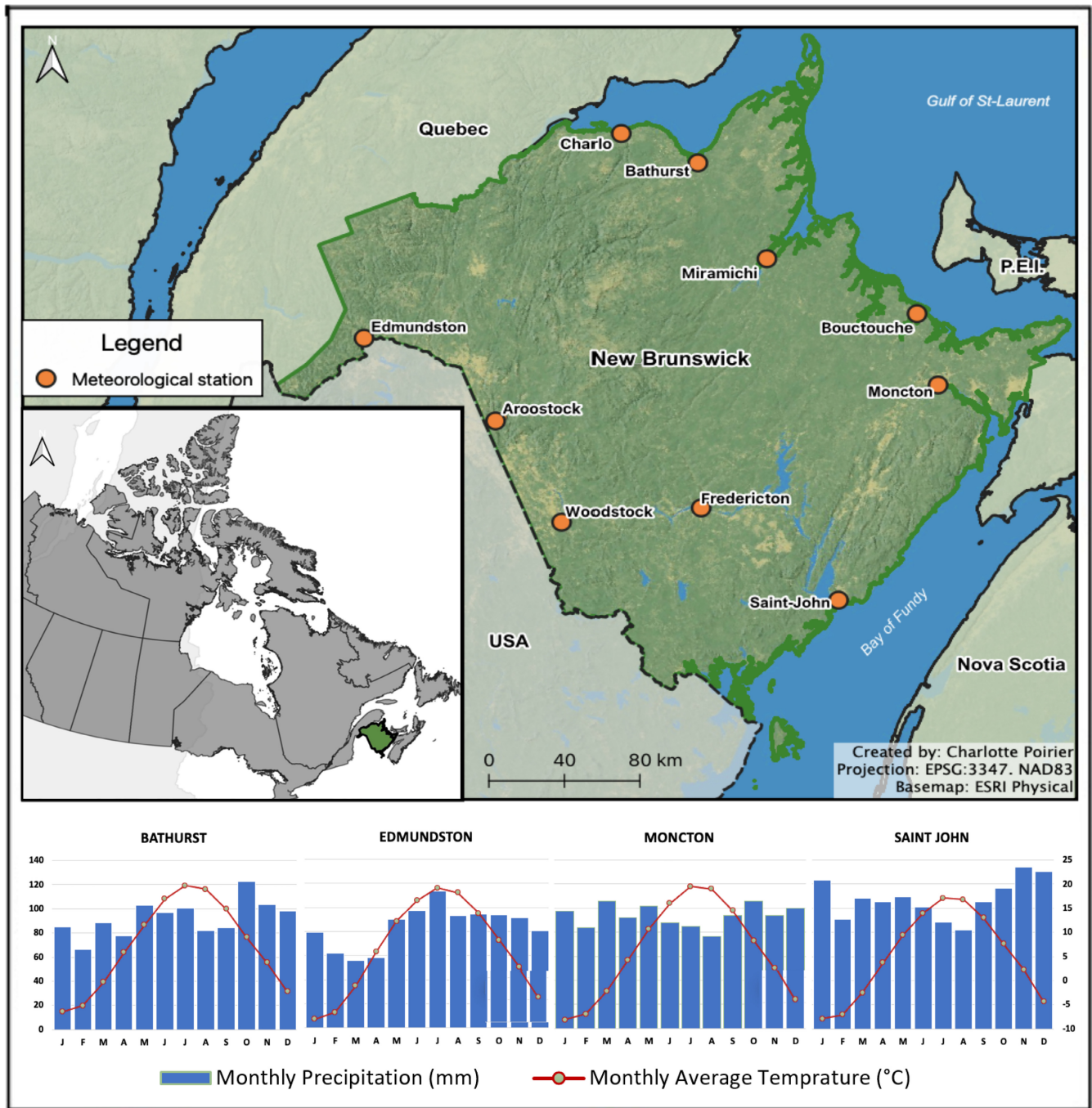


FIGURE 1 Location map of the study area with meteorological station distribution and ombrothermic diagrams of climatic normal from 1981 to 2010 for Bathurst, Edmundston, Moncton and Saint John (Environment and Climate Change Canada, 2021). [Colour figure can be viewed at wileyonlinelibrary.com]

challenging to pinpoint (Dubreuil, 2005). Adapting to droughts is critical when considering the current dependence of human activities and ecosystem health on water availability (Bonsal et al., 2004).

Some studies were made on the historical evolution of climatological variables such as temperature and precipitation on a larger geographical scale. To better circumscribe climatic variability in the province, we analyse

temperature and precipitation trends, which helps us to better understand the context in which drought episodes occur. Nevertheless, there is little literature on the historical portrait of droughts in the eastern provinces of Canada (Tam et al., 2018), and fewer targeting the specific territory corresponding to the province of New Brunswick. Effectively, this exposes a common problem related to the lack of local drought data and amplifies the

importance of regionalizing climate studies, which are still scarce in Canada.

This study aims to provide a historical picture from 1971 to 2020 of the state of droughts in New Brunswick from a climatological perspective. Specifically, we wish to identify statistically significant trends in the Standardized Precipitation Index (SPI) and Standardized Precipitation-Evapotranspiration Index (SPEI). We applied nonparametric trend tests such as Mann–Kendall and Sen's Slope for 10 stations located in New Brunswick. Our results indicate that a slight decrease in precipitation (increase in drought) occurred for six stations between 1971 and 2020. The three driest summers (2020, 2001 and 2004, respectively), according to the SPI and SPEI indices, occurred in the second half of the study period. This period also corresponds to a period of increasing population in many NB municipalities, putting additional pressure on water resources. Our results show that municipalities need to consider droughts in their climate adaptation plans and make adjustments to their planning and managing water resources in cities in the most affected areas, which they currently do not do.

2 | DATA AND METHODS

2.1 | Study area

The study area is in Eastern Canada and consists of the province of New Brunswick (Figure 1). Four ombrothermic diagrams (Figure 1) illustrate the variability of precipitation and temperature over the year in various parts of the province. Bathurst is in the northwestern part of the province, Edmundston in northeastern NB, Moncton in the south-east, while Saint John is in the extreme south-central part near the Bay of Fundy. The size of the territory is approximately 73,440 km². New Brunswick comprises uplands, lowlands and hills, but the two main geomorphological zones are hills and plains (Government of New Brunswick, 1995). The Appalachian Mountain Range extends through the north-central part of the province, where the highest peak is Mount Carleton, with a maximum altitude of 817 m. The area has a 5500 km coastline representing more than 87% of the NB border. The territory is interspersed in all directions by a vast hydrographic network. Its most important river is the Saint John River, which flows nearly 674 km long and acts as a physical border with Quebec province (Canada) and Maine state (USA).

Geographical features such as altitude, latitude and longitude play a decisive role in characterizing New Brunswick climates (Fortin & Dubreuil, 2020; Groenewoud, 1984). Two central climates are recognized

in the province. A warmer maritime climate with milder winters and summers can characterize the southern part. These thermal characteristics are primarily affected by wet air inputs from the cold-water basins surrounding NB, the Atlantic to the east and the Bay of Fundy to the south (Government of New Brunswick, 2010b). The region further north, especially on the west side, is more influenced by a continental effect. This influence leads to colder winters and warmer summers than in the southeastern part of the province, resulting in a continental climate. Areas with higher elevations, such as uplands in the northwestern part of the province, are generally colder during wintertime and receive more precipitation as snow, such as Edmundston (Figure 1). Adverse conditions apply to lower-lying areas in the southeastern region for Moncton or Saint John (Figure 1). These areas receive more precipitation (rain and snow) annually (Government of New Brunswick, 1995). The Caledonian Mountain range in the province south affects the climate by blocking both sides of this physiographic obstacle (Fortin & Dubreuil, 2020).

In NB, many weather patterns bring storms and heavy precipitation, most arriving either from the southwest (Great Lake, Hatteras, Gulf and Colorado lows) or the northwest (Mackenzie and Alberta lows)—their influence changes according to the season. For example, some systems arriving from the southwest, such as Hatteras lows, are more intense in winter (Davis et al., 1993). However, these low-pressure storms generally pass south of Nova Scotia and Newfoundland and rarely affect New Brunswick. Most storms associated with low-pressure systems deviate further north during summer and are less significant for NB, while convection storms are more frequent. Compared to precipitation events, it is more challenging to determine which weather systems are responsible for drought. However, circulation patterns in the upper atmosphere are a significant factor in triggering droughts. These can include blocking effects (stationary systems mid-tropospheric ridge) that prevent the passage of rain-generating systems or teleconnections such as El Niño that can reduce the amount of precipitation received during the summer as Bonsal and Lawford (1999) observed in the Canadian Prairies.

2.2 | Data source and data processing

To calculate the SPI and SPEI, we used the monthly weather data from 10 meteorological stations from the national network located in New Brunswick (Figure 1) from 1971 to 2020 that were obtained (Environment and Climate Change Canada, 2021). Downloaded data come directly from the Environment Canada website:

TABLE 1 The proportion of missing data for monthly precipitation (Pt), minimum temperatures (Tn) and maximum temperatures (Tx).

Variables	% of missing data by station									
	A	Ba	Bo	C	E	F	Mi	Mo	SJ	W
Tn	13.1	2.79	3.28	1.53	5.78	1.64	1.09	3.55	4.37	2.93
Tx	12.93	2.79	2.35	1.53	5.44	1.64	1.09	3.55	4.37	2.75
Pt	14.36	3.7	6.34	5.91	3.34	3.05	4.71	2.04	4.37	2.87

Abbreviations: A: Aroostook; Ba: Bathurst; Bo: Bouctouche; C: Charlo; E: Edmundston; F: Fredericton; Mi: Miramichi; Mo: Moncton; SJ: Saint John; W: Woodstock.

https://climat.meteo.gc.ca/historical_data/search_historic_data_f.html. Most data were already homogenized, but for those where it is not the case, we used the same approach as that described by Wang et al. (2010) and Vincent et al. (2012) for temperature and Mekis and Vincent (2011) for precipitation. Based on data availability and quality criteria, we initially selected 10 stations out of a potential of nearly 50. We have tried to keep as many stations as possible in our sample, including all those that have sufficient data representative of the various climates in the province (Fortin & Dubreuil, 2020). Following WMO (2021), different quality control tests for climate data such as constraints, consistency, heuristics, data provision or statistical tests, are available. In this study, we used the maximum/minimum, mapping-based spatial and linear regression spatial statistical tests. These tests enable selected historical data to be analysed statistically, aiming to detect and identify inconsistent, improbable or impossible records. In addition, various non-climatic factors can affect the quality and quantity of climate data, including measurement systems, relocation, changes in instrumentation, exposure conditions and observers (Acquaotta et al., 2019). It is, therefore, crucial to ensure the quality of the data used when analysing climate variability to avoid noise (non-climatic factors) interfering with the signal (climate trend).

Moreover, we verified that no significant changes occurred that might disrupt the continuity of the findings, such as the relocation of a weather station. It is sometimes possible to use incomplete series to do specific statistical tests if the proportion of missing data is relatively low. Only the weather stations for which less than 20% of the daily data were missing in the time series were analysed. Many previous studies have used a similar threshold (Fortin & Héту, 2014; Giaccone et al., 2015; Haylock et al., 2008). The data collected included monthly precipitation, monthly average minimum temperatures and monthly average maximum temperatures. The lack of representation for the central part of the province is attributable to the absence of meteorological stations in that area. If ECCC did not assume quality control (Mekis & Vincent, 2011; Vincent et al., 2012), we made it and replaced missing values using the Inverse Distance Weighted (IDW) method

(Shepard, 1968) if necessary. There are some possible limits to this interpolation method. For example, the quality of the results obtained may be reduced if an uneven distribution of points is used or if there are outliers in the data. When using this approach, particular attention must be paid to the data quality used to replace missing values.

Table 1 shows the proportion of missing data in the time series for each station.

2.3 | Calculation of SPI and SPEI

McKee et al. (1993) developed the Standardized Precipitation Index (SPI), which identifies the intensity and moment of formation and dissipation of a drought episode from quantifying precipitation deficits, which can be done at different time scales. The SPI is used worldwide due to its simplicity, which requires only one input parameter (precipitation) and is recommended by the World Meteorological Organization (2016).

The calculation of the SPI is based on the work of Thom (1966), who determined the gamma distribution to be consistent with the climatological precipitation time series. Essentially, the SPI/SPEI indices are calculated as follows:

$$\frac{(P_i - P_m)}{S}, \quad (1)$$

where P_i is the rainfall (or rainfall and temperature) of month or year i , P_m is the average rainfall (or rainfall and temperature) of the series over a time scale considered S for the standard deviation of the series over the time scale considered. However, certain conditions limit the use of the SPI since it assumes that series follow a normal distribution. In certain circumstances, such as extreme precipitation events, series do not necessarily follow a normal distribution, which may affect the results obtained. In addition, series covering a sufficiently long period are required to ensure accurate long-term averages and standard deviations. In regions with limited data quality or quantity, this can compromise the results obtained.

TABLE 2 Definition of drought conditions for SPI and SPEI indices.

Levels	Description	Conditions
1	Near normal	0 to -0.99
2	Moderately dry	-1.0 to -1.49
3	Severely dry	-1.5 to -1.99
4	Extremely dry	-2.00 ≤

The normalized precipitation and evaporation index (SPEI) (Vicente-Serrano et al., 2010) is fundamentally similar to the SPI except for considering potential evapotranspiration (PET). This more modern and versatile index is increasingly used for monitoring climate change impacts (WMO, 2016). Hargreaves and Samani (1985) proposed a simplified water balance calculation approach. The Hargreaves method (Hargreaves & Samani, 1985) now estimates potential evapotranspiration from the maximum and minimum temperature variables.

The original Hargreaves equation is (Equation 2):

$$PET = K_g \times R_s (T_c + 17.8), \quad (2)$$

where PET (potential evapotranspiration), R_s (solar radiation), T_c (average temperature) and K_g is the calibration coefficient. Hargreaves and Samani (1985) present an equation for estimating R_s from extraterrestrial radiation, R_A , and the measured temperature range (Equation 3):

$$R_s = K_{RS} \times R_A \times TD^{0.5}, \quad (3)$$

where R_s and R_A are from the same units. K_{RS} is a calibration coefficient and TD is the average maximum temperature minus the average minimum temperature. The combination of Equations (2) and (3) gives the following results (Equation 4):

$$PET = K_{ET} \times R_A \times TD^{0.5} (TC^{0.5} + 17.8). \quad (4)$$

Once the PET has been calculated, we want to obtain the difference between P (precipitation) and PET for a month or year i (Equation 5):

$$D_i = P_i - PET_i. \quad (5)$$

We then estimate the water surplus or deficit (D_i) for the month or year under analysis. The calculated D_i values are then aggregated at different timescales (1, 3, 6 or 12 months), following the same procedure as for the SPI.

SPI and SPEI can be classified on four levels according to their range of values (Table 2). In addition, we analysed 1-, 3-, 6- and 12-month timescales in our study.

To verify the significance of the trends for both indices and the meteorological data variables, the nonparametric Mann–Kendall test (Kendall, 1948; Mann, 1945) was applied. This test, recommended by WMO (2016), determines the presence or absence of significant (p value <0.05) monotonous trends.

2.4 | Other methods

In addition to assessing the presence of a trend (statistically significant or not according to the hypothesis test), other statistical tests were applied, such as τ (tau) test, which makes it possible to identify the direction of the upward or downward trends. The magnitude of the trend was estimated by the nonparametric Sen's slope method (Sen, 1968).

Following the methodology above, the meteorological variable, the SPI and the SPEI index time series (all complete from the previous steps) were averaged at a monthly timescale over all 10 stations to characterize the dry conditions in all New Brunswick.

3 | RESULTS AND DISCUSSION

3.1 | Meteorological variables trend analysis

3.1.1 | Precipitation analysis

Four of the 10 weather stations show a statistically significant positive trend for increased precipitation. Conversely, the remaining six stations show a negative trend indicating decreased precipitation, but only four of them are statistically significant (Table 3). From a spatial perspective, observations made from stations in the southern part of the province generally indicate a positive statistically significant precipitation trend. When comparing our results with other studies (Environment and Climate Change Canada, 2019; Roy & Huard, 2016; Thistle & Caissie, 2013; Zhang et al., 2000), it is unclear if there are some precipitation trends (increase or decrease) in the Atlantic region. This lack of consensus is not restricted to our study area because trend detection for precipitations is generally less evident (Vincent et al., 2018). It can significantly vary with the number and location of weather stations and the period considered.

According to an assessment made of eastern Canadian provinces, an increase in average annual

TABLE 3 Tau values from Mann–Kendall's test for meteorological variables for 10 stations in New Brunswick.

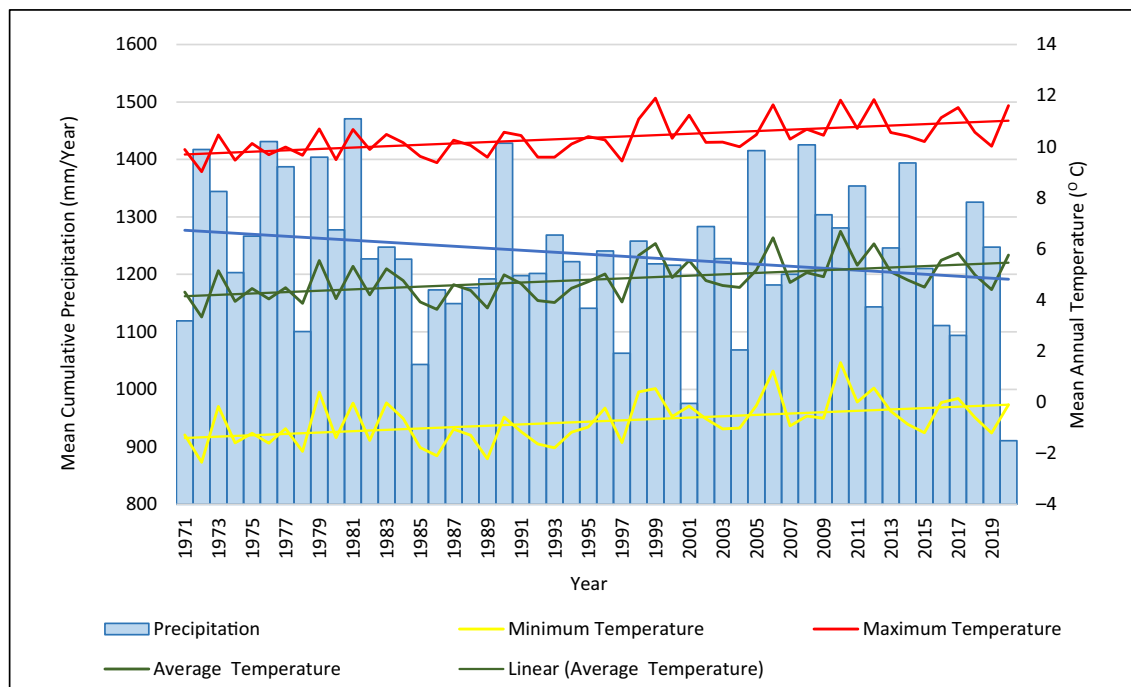
	EDMUNDSTON	AROOSTOOK	BATHURST	BOUCTOUCHE	CHARLO	MIRAMICHI	FREDERICTON	MONCTON	SAINT JOHN	WOODSTOCK
Precipitation	-0.027	0.031	0.011	-0.025	0.012	-0.074	-0.065	-0.073	-0.055	0.019
Temp. Max	0.031	0.038	0.033	0.040	0.032	0.027	0.022	0.038	0.046	0.002
Temp. Min	0.043	0.044	0.015	0.010	0.015	0.041	0.039	0.044	0.038	0.033

Note: For tau values, results written in bold indicate a significant trend at the 0.05 level.

precipitation of approximately 11.3% was observed from 1948 to 2016 (Environment and Climate Change Canada, 2019), while the study by Zhang et al. (2000), which indicates results at a smaller scale for the Canadian area, shows little to non-significant increasing trends and even some tiny decreasing non-significant trends, especially for the southern part of the province for the period from 1948 to 2003 (Natural Resources Canada, 2009). Recently, Vincent et al. (2018) demonstrated that trends varied considerably across the province and often contradictions based on several indices between 1948 and 2012. For example, the number of days with rain, snow and precipitation (rain and snow) increased in northern NB but decreased in the south. This example is consistent with our results and highlights the difficulty of adequately representing trends in precipitation, even at a relatively fine scale.

Indeed, the study's time scale seems to have a considerable impact on the results exposed in the work of Thistle and Caissie (2013). For example, these authors have shown many contradictions between the trends over the seasons. Spring significantly increased, winter and summer significantly decreased, while fall had no significant trend. The total annual precipitation trends in change per decade were calculated for six meteorological stations in New Brunswick over three different time scales (30, 60 and 110 years). For NB, the shortest study period showed mostly non-significant trends; the Saint John station had a >10% decreasing trend, the only station with a significant change. In contradiction, the 110-year period showed important, primarily increasing trends. For the 60 years (1951–2010), only the Bathurst station registered a significant increase of 0%–5%, while the Saint John station registered a substantial decrease of 0%–5%. The four other stations (Aroostook, Fredericton, Moncton and Miramichi) reported no significant trend. Compared to its neighbours, results concerning the province of New Brunswick are like those found for Nova Scotia and Prince Edward Island, which show very few significant trends. Compared with the Gaspé Peninsula and Newfoundland, a greater contrast can be observed, where more significant positive trends were registered (Thistle & Caissie, 2013).

The 60 years of Thistle and Caissie (2013) study, almost matching our 50-year study period, shows comparable results when evaluating the same stations. Furthermore, our study, calculated over a more recent time frame, shows dryer trends exposed in the 30 years study by Thistle and Caissie (2013). As indicated in Figure 2, the sub-time of 1971 to 1985 seems to have registered higher total annual precipitations, with 1976 and 1981 being the years with the most rain and the last 20 years of our study period recorded the lowest yearly rainfall,



*Full linear trendline indicating a significant trend.

FIGURE 2 Diagram the total annual precipitation and mean temperature from 1971 to 2020 for 10 stations in New Brunswick. [Colour figure can be viewed at wileyonlinelibrary.com]

with 2001 and 2020 being the dryer years. As Gangarde et al. (2023) point out, various factors, such as the choice of statistical tests and the length of the period chosen can affect the results obtained when analysing time series trends. For example, the period considered for examining the trend could show different significance or trend slopes (short-term trend), which could be overlooked in the case of an analysis of an ensemble covering a longer period (long-term trend). The results obtained should therefore be interpreted with caution.

The evaluation of trends includes difficulties mainly attributed to the discontinuous nature of precipitation and their diversity of states (rain, snow and freezing rain) (Natural Resources Canada, 2009). Other studies used precipitation variables such as annual maximum rainfall (Burn & Taleghani, 2013), maximum consecutive dry days and very wet days (Vincent & Mekis, 2006). They also show conflicting results over time and space scales, thus corroborating this non-significant mix of trends over New Brunswick (Mekis & Vincent, 2011).

3.1.2 | Temperature analysis

As for the temperature variables, three periods seem to emerge (1971–1984, 1985–1998 and 1999–2020) in

Figure 2. The mean temperature appears to increase throughout the study period, with a slower increase occurring from 1985 to 1998. This period coincides with a colder period from 1985 to 1993, as Larouche and Galbraith (2013) identified. The more recent sub-period (1999–2020) registers a higher mean temperature and fewer low mean temperatures; this confirms what was reported in the literature with a slight increase in temperature in the latest years (Larouche & Galbraith, 2013; Thistle & Caissie, 2013). Indeed, the years with the highest mean temperature over the last 50 years are 2010, 2006, 1999, 2012 and 2020. The 14 years with the lowest mean temperature correspond to the 20th century. Although no significant trend was identified, the Mann–Kendall test applied on maximum and minimum temperatures for all weather stations used in this study indicated an increasing trend (Table 3). In their study, Zhang et al. (2000) reported a similar increase throughout 1900–1998, showing minor but non-significant positive trends for mean temperature over all New Brunswick.

3.1.3 | Drought in the 1971–2020 period

2020, 2001 and 2004 are the driest years of the last 50 years (Figure 3a). SPI and SPEI have been identified

these years similarly with very similar values. For 2020, the SPI mean (-2.02) was slightly higher than the SPEI mean (-2.12), which both can be classified as extremely

dry conditions. All 10 stations had registered dry conditions with the SPEI index, with six identifying extremely dry conditions (Figure 3b). As for the SPI

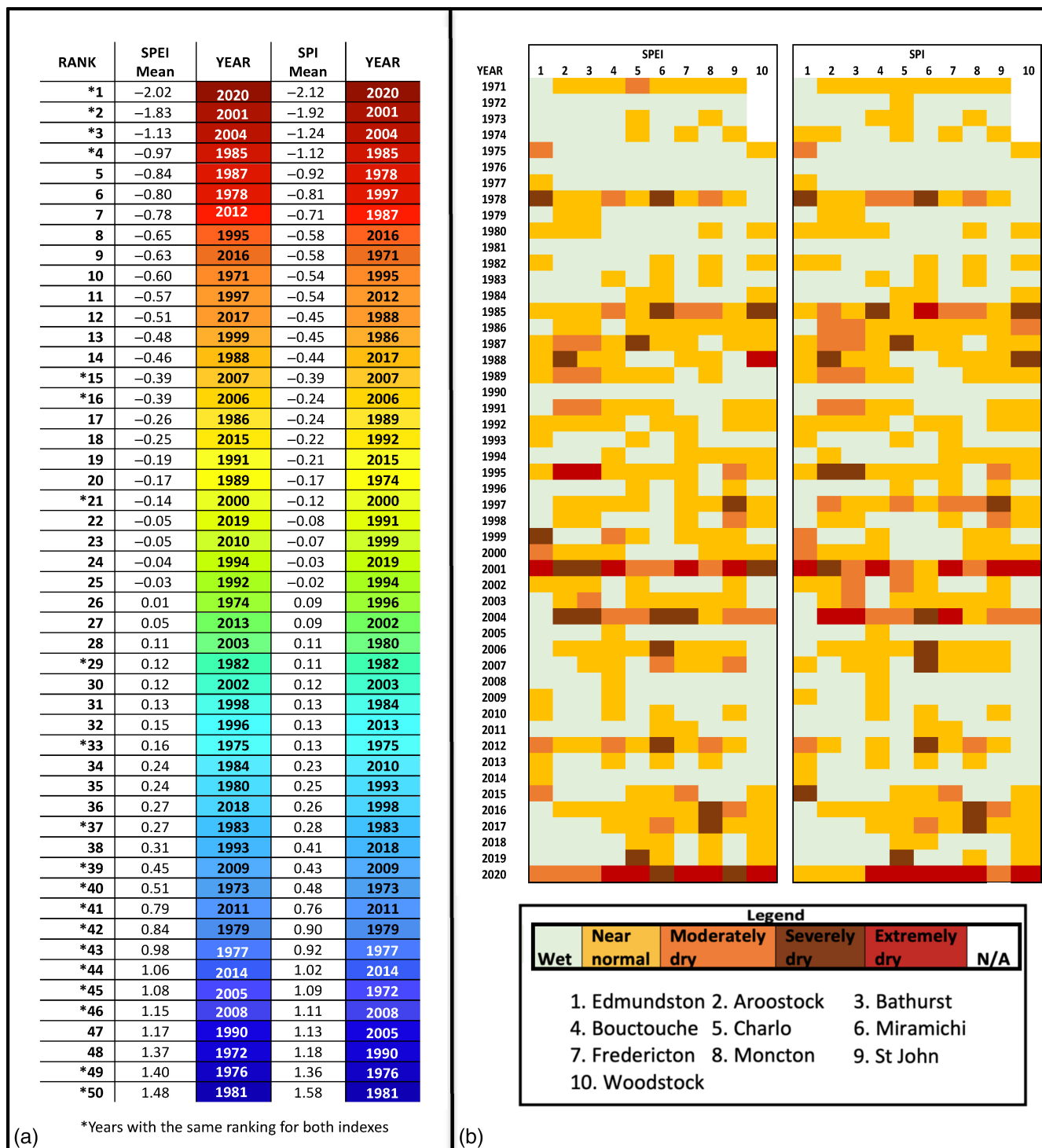


FIGURE 3 (a) Comparison of SPEI and SPI mean values (12 months) from 1971 to 2020 compared to their normal. The colours allow us to visually appreciate the transition from the driest years (in dark red) to a gradual decrease passing by the orange, yellow and then to the green for the relatively neutral years until the most watered years with the darker blue. (b) Chronological graphic method of information processing (MGCTI) applied to annual mean values of SPEI and SPI indices for 10 New Brunswick meteorological stations from 1971 to 2020. [Colour figure can be viewed at wileyonlinelibrary.com]

index, eight stations detected dry conditions counting seven stations with extremely dry conditions. The second driest year was 2001. Here, with the SPEI index, nine stations registered dry conditions, with only two stations rating extremely dry conditions. For 2004, the same eight stations identified dry conditions with both indices. However, three stations were ranked with extremely dry conditions with SPEI, and one was identified with SPI. 2020 and 2001 also correlate with the lowest annual precipitation, with 2003 receiving 911 mm, 2001 975 mm and 2004 in the 5th rank with 1069 mm (Figure 2). Although the three driest years occurred during the last decades, the moderately dry conditions seem to be even when comparing the first (1971–1995) and the second half (1996–2020) of the study period. Maybank et al. (1995) provided a detailed assessment of droughts in Canada, which clearly showed that the Canadian Prairies were heavily affected by this phenomenon, while the Eastern part of the country remained marginally affected. The only drought period reported having affected the Maritimes was in 1984 and only for Nova Scotia. However, 1984 ranks 31st and 34th in the SPEI and the SPI indices, respectively. The period of this latter study is different from ours. As mentioned above, the period post-2000 has seen an increase in temperatures and conditions conducive to a rise in drought episodes, which seems to be transposed when analysing our results illustrated in Figure 3.

Several studies have focused on identifying patterns and explanatory causes of droughts in North America (Aryal & Zhu, 2021; Barlow et al., 2001; Woodhouse et al., 2009). Yang et al. (2020) attempted to determine how teleconnections in Canada could explain spatial and temporal variability of droughts. Their results indicate that droughts are generally more negatively correlated with El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) after the 1970s while more positively correlated with the Atlantic Multidecadal Oscillation (AMO) and Arctic Oscillation (AO) after the 1980s. These causes could explain the recent drought events detected by our study.

3.1.4 | SPI and SPEI trend analysis

The monthly average values for both SPI and SPEI evolution through the study period of 1971 to 2020 all indicated a decrease in the index value; this means there were dryer conditions throughout time. While the shorter time scale of 1 month did not show a significant trend, all the other time scales (3, 6 and 12 months)

indicated a significant negative trend. The more extended the time scale, the higher the magnitude of the trend. In comparison, Gurrapu et al. (2014) analysed the correlations between the flow of several rivers in Canada and the SPI and SPEI and obtained different results, especially for the more extended period (12 months). Their results show little difference between the two indices as we do. Still, they also indicate that the SPEI proves to be a better choice for assessing the influence of temperature increases on future drought. These authors observed that the SPEI strongly correlates with streamflow in late spring, summer and early fall at time scales of 6 and 9 months but shows weaker correlations for shorter (1, 2 or 3 months) or more extended (greater than 12 months) periods. Seasonal river flows vary according to the hydrological cycle of the study area, including atmospheric systems, clouds, wind, precipitation, evaporation, the natural water reservoir system and runoff (surface and groundwater). All these elements vary according to the characteristics of the different study areas. For example, the climate in the Prairies varies from arid to sub-humid, while in New Brunswick, the climate is described as humid continental.

Moreover, Gurrapu et al. (2014) noted that the SPI, which is based solely on precipitation quantity, is less sensitive than the SPEI, which allows evapotranspiration to be considered since it also uses temperature data. Nevertheless, temperature variability on the Prairies is low, but when temperatures rose, the SPEI was more responsive than the SPI. In addition, the length of the study period is another factor likely to explain the discrepancies obtained between trends calculated on time steps of 1, 3, 6 and 12 months. In addition to the length of the period, there are differences in the periods analysed, notably in our study we used more recent data (up to 2020). The 2010–2019 decade was warmer than 2000–2009, which may partly explain the discrepancies between our results and those of Gurrapu et al., 2014.

Trends in SPI and SPEI indices should be interpreted as indicators of increasing or decreasing surface water amount in response to climatic conditions. In Canada, droughts generally occur during the summer season and can spill over into spring and autumn but rarely occur during the winter due to snow cover. As Gurrapu et al. (2014) proposed, such seasonal variability could be caused by the moisture loss to evapotranspiration during spring/summer, with the increasing temperatures accounted for by the SPEI. However, a winter with little snow can limit groundwater recharge and, in the longer term, lead to droughts several months later.

3.2 | Temporal and spatial extent of drought

3.2.1 | Temporal evolution in the SPI and SPEI

When looking at the 12-month lag, a good indicator for hydrological drought, both indices identified the 1982 to 1998 driest period well (Figure 4). The second dry period determined by SPEI was from 2001 to 2007, while for the SPI, it was from 1995 to 2007. As for the last decade, the SPEI index showed significantly negative values, presenting a dry period from 2010 to 2020. For the SPI, the previous 10 years present equivalently distributed low positive and low negative values except for 2020, which indicated the lowest SPI value over 50 years. The sub-time period of 1971 to 1982 was the least affected by drought than the rest of the timeline. More so for the SPEI than the

SPI, the longer the timescale, the more pronounced the drought trend was. Indeed from 2001 to 2020, there was a very high presence of low SPEI values showing an increase of frequency in drought events which is not as present for the SPI values. This situation could be justified by including the temperature variable in the SPEI calculation. As previously presented, there has been an indication of increasing temperatures in New Brunswick, which have been significantly more significant in recent years. The SPEI index generally showed more extreme values than the SPI index all-timescale.

3.2.2 | Spatial variations in the SPI and SPEI

The results of the spatial variation analysis appear to lack any clear conclusion. Indeed, the minimal number of stations representing the study area makes it difficult to see

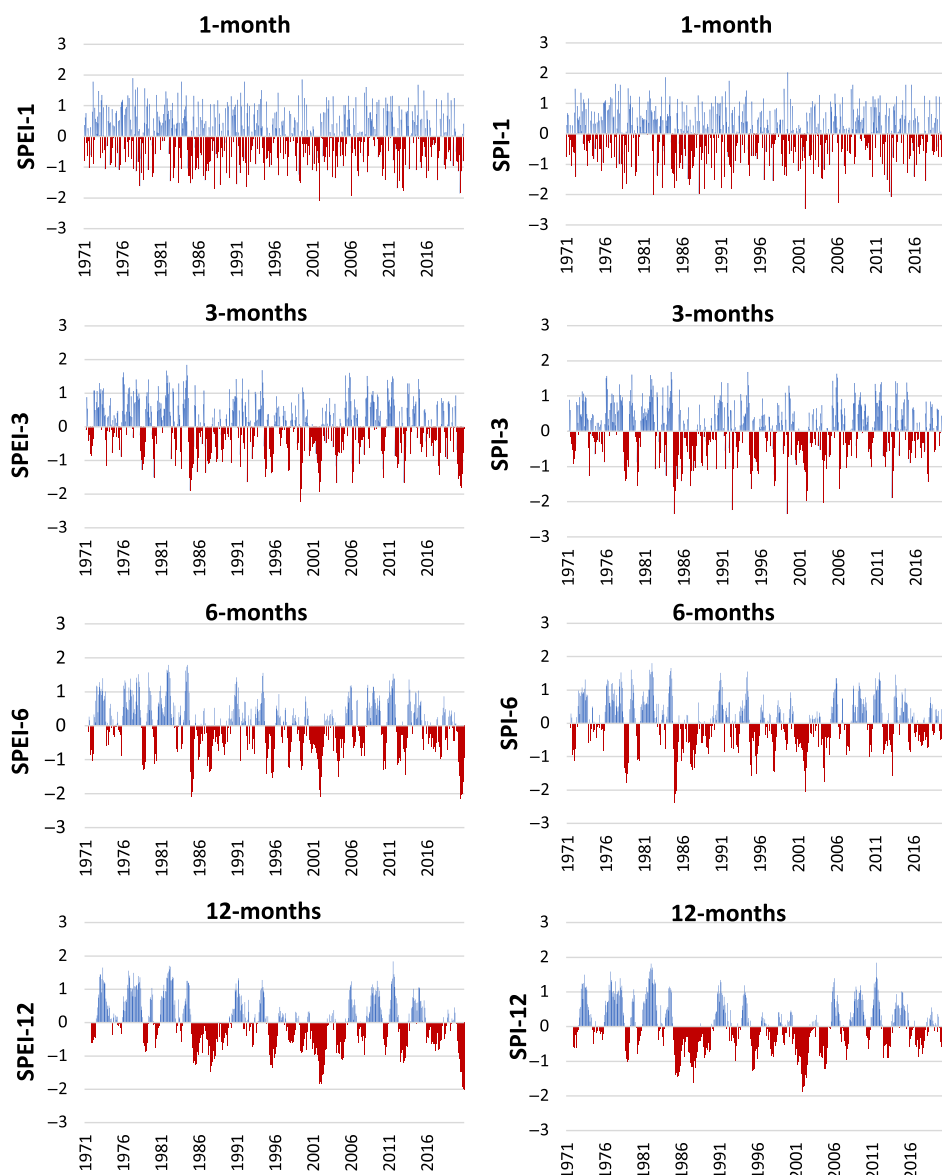


FIGURE 4 Temporal evolution of SPEI and SPI mean value of the 10 meteorological stations at 1-, 3-, 6- and 12-months lags, respectively. [Colour figure can be viewed at wileyonlinelibrary.com]

any spatial coherence. For the SPEI index, the research showed that four stations (Moncton, Saint John, Fredericton and Miramichi) stand out with the highest increase of dry conditions and for the consistency of the significantly negative trend. These stations are located furthest south, except Miramichi, which is in the eastern centre of

the province. The four stations indicating less of an increase in drought include Aroostook, Bathurst, Charlo and Woodstock. Indeed, these stations did not register any significant trends. Even so, some trends are positive. In this case, the proximity of these stations is not a notable characteristic, Bathurst and Charlo being located

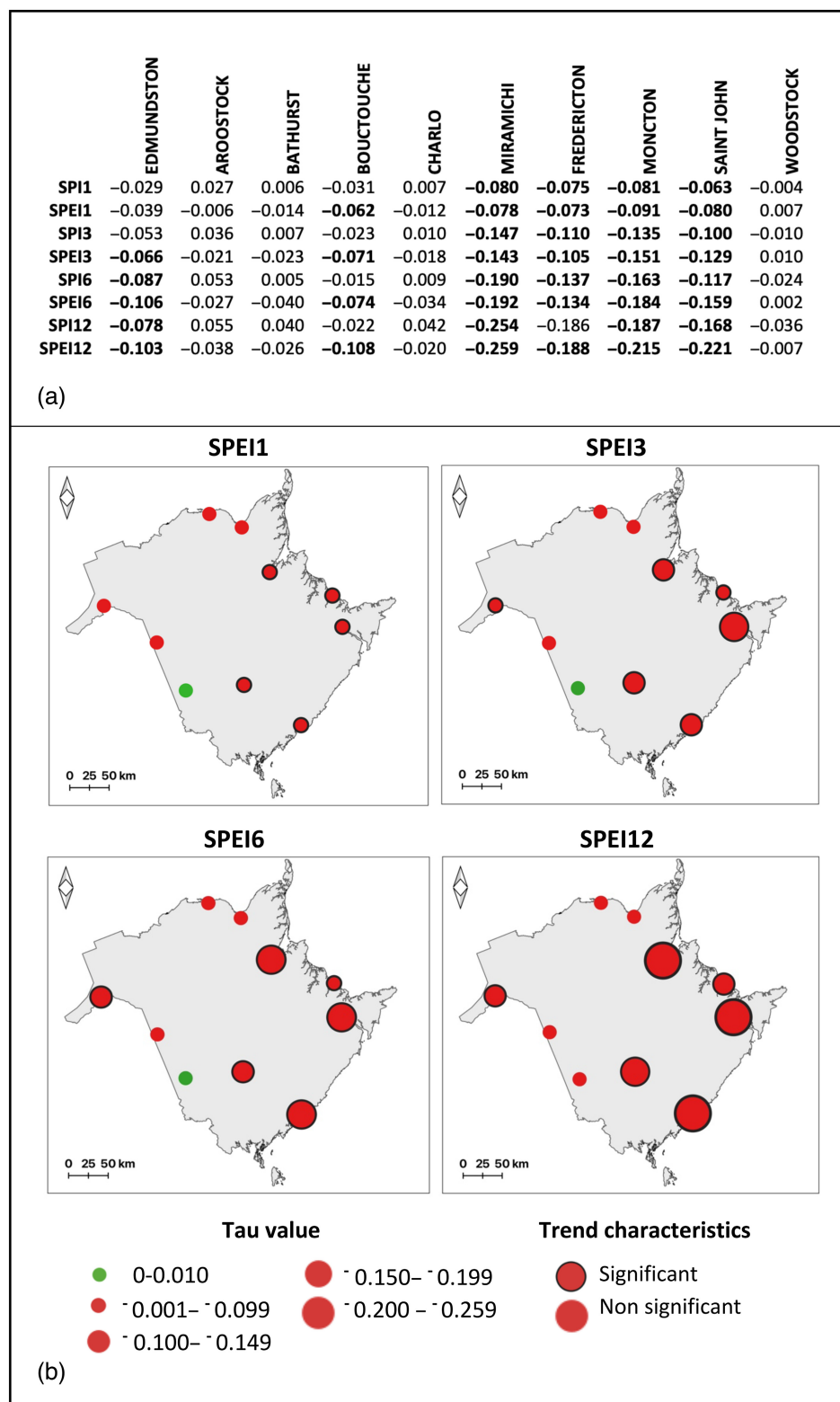


FIGURE 5 Tau values from Mann-Kendall's test for SPI and SPEI at 1, 3, 6 and 12 months for 10 stations in New Brunswick with the spatial distribution for the SPEI values. [Colour figure can be viewed at wileyonlinelibrary.com]

Centre-North while Aroostook and Woodstock Centre-West (Figure 5).

Edmundston received less rain over the study period because it is in the province's centre in dry conditions. All trends are negative, but significantly negative trends have been identified for 6-month and 12-month scale indices. At the other end of the spectrum, Saint John is the station that registered the highest total rain amount over the last 50 years and registered the most significant negative trend. However, given the limited number of stations available for our analyses, it is impossible to draw consistent spatial conclusions.

4 | CONCLUSIONS

This historical drought analysis of the province of New Brunswick between 1971 and 2020 is based on 10 meteorological stations. Two climatological drought indices, SPI and SPEI, were applied over various temporal scales (1, 3, 6 and 12 months) to evaluate multiple drought characteristics, such as trends and patterns. Temperature and precipitation trends were analysed. The main conclusions from the analyses are the followings:

- As a global assessment, the province of New Brunswick has seen a downward precipitation trend over the study period. More specifically, six out of ten stations showed a negative trend, with Miramichi, Fredericton, Moncton and Saint John stations indicating significant results. The Bathurst, Charlo, Aroostook and Woodstock meteorological stations showed a slight non-significant positive trend. These results correlate with other studies suggesting a mix of non-significant precipitation trends for the province for the same approximate time.
- Both maximum and minimum temperatures indicated a non-significant upward trend for all stations.
- Over the last 50 years, the driest summers are 2020, 2001 and 2004. Both the SPEI and SPI identified these years.
- The average value for SPI and SPEI evolution throughout the study period of 1971 to 2020 indicated a decrease in index values. Every time scale longer than 1 month showed significant decreasing trends. The longer the time scale, the higher the magnitude of the trend. Although the annual mean for both indices was similar, the SPEI mean values were slightly less elevated, indicating dryer conditions.
- The temporal evolution of the SPI and SPEI were similar at various timescales, but there were still slight differences in the fluctuation value. Both indices identify 1982–1998, 2001–2007 and 2020 as periods with the highest dry conditions over the last 50 years.

Differences between indices are more present in the second half of the study period. SPEI shows more critical and frequent drought conditions than SPI, whose values were more evenly distributed between wet and dry conditions.

- As for spatial distribution, four stations stand out with the highest increase in dry conditions and the consistency of the significantly negative trends for the SPEI value: Moncton, Saint John, Fredericton and Miramichi. Stations in the northern part of the province showed lower trends except for the Woodstock station, which indicated a non-significant positive result for the time scale of 1-, 3- and 6 months.

Predictions specifically made for New Brunswick by Roy and Huard (2016) suggest an increase in annual precipitation 2080 from the RCP8.5 scenario, between 12,06% and 13,42%. These values are in the average range of those predicted by ClimateData.ca (2023), which anticipates an increase in annual precipitation of between 42 mm and 324 mm from 2071 to 2100 under climate scenario RCP 8.5 of CMIP6. These values correspond respectively to increases of between 3.4% and 21.8%. The RCP 8.5 scenario assumes high emissions, with few restrictions on future emissions. In the model this rapid growth in emissions continues and only stabilizes at about 2250. Under this scenario, Canada would experience an increase in average temperatures of about 6.3°C by the end of the century. For precipitation, there is much variability across regions. However, according to climate scenario RCP2.6 (a scenario that assumes modest increases in emissions) of CMIP6, increases in total precipitation in the province would be more modest (between 19 and 204 mm) between 2071 and 2100.

Our study indicates a possible slight drought-increasing trend in New Brunswick using the Mann-Kendall test from 1971 to date. However, droughts are predicted to decrease according to some climate scenarios for the North American region (Tam et al., 2018; Yang et al., 2020; Zhao et al., 2020). Nevertheless, many of the changes in the hydrological cycle caused by global warming could explain an increase in droughts, as has been the case elsewhere in the world. The difference in precipitation, even if positive, is offset by the growth of potential evapotranspiration leading to a slight rise in drought events. Increased demand for water due to population growth in urban areas and for irrigation in agricultural areas are also factors that may exacerbate the water availability problem in the near future. It is crucial to implement adaptation strategies for water management now to avoid supply problems, as is already the case in several other regions of southern Canada (Bonsal et al., 2011; Tam et al., 2018).

As a result of the work done in this study, new information is now available to help further the understanding of the temporal and spatial characteristics of drought in Eastern Canada. In addition, Yang et al. (2020) studied the duration of droughts in Canada. Their results suggest that southern and eastern Canada have experienced more extended droughts in recent decades, mainly since the 1990s, which is consistent with our results. In addition, we provide valuable knowledge for future water resources and natural hazard management. Based on observing past droughts, we can expect that drought frequency will be more prevalent in the future. To better understand how droughts are likely to affect communities and ecosystems, our results can be used to assess drought vulnerability by calculating a multi-criteria index that combines variables related to exposure, adaptation and sensitivity, as has been done for floods (Duhamel et al., 2022; Sarker et al., 2022). In this case, our data will provide information on the exposure to droughts (frequency, duration and intensity) to which complementary variables will be added, such as the damage caused by the events (crop losses, etc.).

One of the main limitations of our study is the use of data from meteorological stations (10 in total). We are aware that the number of stations is limited, but this is due to the application of data quality criteria, as explained above. However, it would be conceivable to use gridded data such as that from CanGRD or Australian National University spline interpolation (ANUSPLIN, see McKenney et al., 2006), which provide interpolated data that can be used to calculate the SPI and SPEI indices. In this case, the spatial distribution of the data would be improved, but it would be data estimated by interpolation rather than observations from stations.

Several avenues of research remain to be explored to better understand the causes and consequences of drought risks in Eastern Canada. Firstly, it seems crucial to develop methods to characterize the spatial variability of droughts better. To this end, the use of gridded data (Candrid or ANUSPLIN) or satellite images (Landsat, MODIS, SPOT, NOAA-AVHRR, etc.) could provide data at a finer spatial resolution for the calculation of drought indices (severity for example). A better understanding of the spatial distribution of droughts would help identify the most vulnerable areas and propose appropriate adaptation solutions. In practical terms, this could enable decision-makers to plan better the quantities of water required to meet the needs of populations and the associated costs (infrastructure for storage, irrigation, etc.) to rehabilitate the environment. Furthermore, we can validate our results and better understand the distribution of droughts at the regional scale, as demonstrated by Nepal et al., 2021;

Seiler, 2007; Zuo et al., 2019. Other avenues of future research to improve our understanding of droughts and their impacts in Eastern Canada include investigating possible links between droughts and atmospheric oscillations such as the North Atlantic Oscillation, the Pacific Decadal Oscillation and the Arctic Oscillation (Yang et al., 2019).

AUTHOR CONTRIBUTIONS

Charlotte Poirier: Formal analysis; data curation; writing – original draft; conceptualization. **Guillaume Fortin:** Writing – review and editing; supervision; conceptualization. **Vincent Dubreuil:** Writing – review and editing; conceptualization.

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How to cite this article: Poirier, C., Fortin, G., & Dubreuil, V. (2023). Spatial and temporal characteristics of past droughts in New Brunswick (1971–2020). *International Journal of Climatology*, 43(15), 7183–7198. <https://doi.org/10.1002/joc.8259>