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Imprints of large-scale climate oscillations on river flow in selected Canadian river catchments

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Abstract

We investigated the impacts of six major climate oscillations on river flow at three stations within the Humber catchments (located in Ontario, ON and Newfoundland and Labrador, NL) from 1970 to 2020 using sensitivity and wavelet analyses. Results indicate that the discharge at East Humber River near Pine (ON) exhibits the highest statistically significant sensitivity, with 0.304 and 0.394 monthly units to the Dipole Mode Index (DMI) and Tropical North Atlantic (TNA), respectively. Monthly significance analysis also highlights the diverse influence of large-scale climate oscillations on river flow across the three locations. Wavelet analysis reveals significant active multidecadal oscillations for the North Atlantic Oscillation (NAO) at East Humber River near Pine, with high spectral power. We confirmed that stations within ON demonstrate sensitivities in a similar direction to the large-scale climate oscillations, contrasting with those observed at NL. The observed inconsistency in the relationship between large-scale climate oscillations and, for instance, NAO at various locations suggests that the impacts of climate oscillations may manifest differently in different regions. Overall, while inland stations exhibit similar sensitivity patterns, the coastal station demonstrates distinct responses, highlighting the importance of geographical context in understanding the impacts of large-scale climate oscillations on river flow dynamics.

KEYWORDS

Canada, river discharge, teleconnection indices, wavelet analysis

1 | INTRODUCTION

Riverine landscapes provide essential ecosystem services needed to balance natural and human-modified environments. Besides these services, rivers also add aesthetics to the environment and serve as natural artifacts (Gow, 1995; Mullins, 2009). In many countries, such as Canada, rivers have shared a long history with the country's development, serving as a space for exchanging goods and services during the European Civilization, means of irrigation, an essential agricultural system for food availability (such as controlled irrigation for continued crop production and growth), and also serving as a means of connectivity via water transportation (Corkal & Adkins, 2008; Hassanzadeh et al., 2014; Innis, 1999; Piczak et al., 2022). Furthermore, to ensure human comfort and sustained livelihood, rivers also serve as sources of clean and renewable energy (Lee, 2011; Wang et al., 2014). From the foregoing, it is evident that rivers are a crucial component of our environment and essential for our sustenance and existence (Fashae et al., 2022). For continued and sustained ecosystem services, we need to ensure that our rivers remain healthy and reliable through consistent monitoring, conscious protection, sustainable restoration practices, and preservation (Baehre et al., 2011; van Lier et al., 2011).

Monitoring rivers consistently is crucial because it allows us to track their health and condition over time (Karr, 1999). Without ongoing observation and data collection, we would not understand how rivers are changing, what threats they face, or how effective our conservation efforts are. Essentially, monitoring helps us detect early signs of degradation, identify emerging issues, and take timely actions to address them. It provides the foundation for informed decision-making, enabling us to implement adequate protection, restoration, and preservation measures to ensure river ecosystems' long-term health and sustainability (Bernhardt et al., 2007; Maddock, 1999). Unfortunately, despite concerted efforts globally to achieve efficient and consistent monitoring of our waterways, the current global monitoring networks are still not enough; this is because the existing networks are inherently biased regarding their distribution and the diversity of rivers (Krabbenhoft et al., 2022). Even though one could argue that some locations are performing better than others in terms of coverage and monitoring schemes, the spatial density, even for most global northern countries, is still not enough coupled with inadequate continuous flow records, changing global climate, and the intrinsic behavior of snow melt-dominated rivers, making careful planning and forecasting for a comprehensive water resource administration difficult to actualize (Nicklow et al., 2010). Furthermore, with the growing population size, increasing urbanization, compounding climate risks and events, and conflicting perceptions on water resources, tensions are building on a just demand and supply of freshwater resources among water users globally (Jury & Vaux, 2007; Li & Velásquez, 2022). Hence, careful planning and understanding of river flow quantities and their forecasts must be emphasized to achieve an effective and efficient water management system.

A key feature in water resources management is an adequate understanding and availability of baseline and long-term flow records, which are hardly available (Bonsal & Shabbar, 2008; Fentaw et al., 2019). For countries such as Canada, the availability of long-term records provides an avenue for a deeper understanding of river flow. It would aid in improving economic and environmental activities such as but not limited to hydroelectric production, freshwater transportation costs, recreation, water quality, and ecological habitat mapping (Bonsal & Shabbar, 2008). Even in the most developed and advanced countries, continuous and uninterrupted river flow records are challenging. Additionally, the behavior of long-term river flow records is highly dynamic and chaotic, which makes prediction challenging (Olusola et al., 2023). Therefore, exploring alternative methods to enhance river forecasting and flow measurement techniques becomes crucial. One promising approach involves leveraging large-scale climate oscillations. Large-scale climate oscillations offer valuable insights into the complex and interconnected factors that influence river flow, making them an essential tool for improving river forecasting and flow measurement techniques.

Understanding the impact of large-scale climate oscillations on rivers is crucial for accurate forecasting and managing water resources. These large oscillations, such as the North Atlantic or the El Nino Southern Oscillations, offer unique insights into river flow properties and influence regional climate patterns. By recognizing the influence of the North Atlantic Oscillation (NAO) or the El Niño-Southern Oscillation (ENSO) on regional climate patterns, forecasters can better anticipate precipitation and temperature shifts as they influence river flow. Incorporating this knowledge into forecasting models allows for more accurate predictions of river discharge, especially in subtropical and temperate regions where these oscillations have significant impacts. For instance, ocean-atmospheric couplings influence atmospheric circulations and, by extension, wind stress. This determines weather patterns such as precipitation and other parameters (Déry & Wood, 2004; Pérez-Ciria et al., 2022; Zhang et al., 2023). Therefore, this study aims to comprehensively investigate the imprints of large-scale climate oscillations, including the Southern.

Oscillation Index (SOI), Tropical North Atlantic (TNA), NAO, Pacific North American (PNA), Western Pacific (WP), and Indian Ocean Dipole Mode Index (DMI), on river flow dynamics within the Humber River Catchments in Ontario, ON, and Newfoundland and Labrador, NL. This research uses sensitivity analysis and wavelet coherence techniques to highlight the relationships between these oscillations and river flow patterns. The selection of these specific oscillations is crucial as they represent critical drivers of climatic variability across different regions, thereby influencing precipitation patterns, temperature fluctuations, and atmospheric circulation dynamics. The inclusion of oscillations such as SOI and TNA, which are associated with tropical climate systems, alongside NAO, which influences North Atlantic weather patterns, reflects the diverse climatic influences on the study area. Moreover, considering the location of one Humber catchment inland, with its discharge into Lake Ontario and another along the Canadian east coast bordering the Atlantic Ocean, provides valuable insights into how these oscillations manifest differently in distinct geographical settings. This comparative approach allows for the differentiation between natural internal variability and externally forced variability, enhancing the robustness of the findings. By integrating sensitivity analysis and wavelet coherence, this study not only elucidates the individual impacts of these oscillations but also explores their interrelatedness and collective influence on river flow dynamics. Ultimately, this research contributes to a better understanding of the complex interactions between large-scale climate oscillations and river systems, facilitating more accurate prediction and management of water resources in the studied regions (Canchala et al., 2020; Chiew & McMahon, 2002; Mishra et al., 2011; Shi et al., 2021).

SOI provides a quantitative measure of phases of the ENSO cycle and is calculated from the variations of monthly mean sea level pressure difference across the Pacific Ocean, from Tahiti (17°31° S and 210°26° E) to Darwin (12°28° S and 130°50° E) in the west. The PNA teleconnection pattern shows the internal mode behavior of the Northern Hemisphere atmosphere as it influences the hydro-climate and ecosystems of the North American Pacific sector. Liu et al. (2020) found increased extreme weather events in North America due to interlinkages among global warming, ENSO, and PNA. The TNA and North Atlantic Oscillation (NAO) are anoma-lies occurring in the North Atlantic Ocean. TNA is the difference between the sea surface temperature in the region (0°˘20° N and 80°˘30° W) and (5° S˘5° N and 170°˘120° W) while NAO is normalized sea level pressure difference between two representative latitudes of 35° N and 65° N, zonally averaged over 80° W˘30° E. Ogunjo and Fuwape (2020) reported that teleconnection patterns have complex interactions. The Western Pacific Oscillation (WP) is a known pressure dipole that influences the pattern downstream across much of North America. At the same time, DMI is the intensity of the Indian Ocean Dipole, represented by an anomalous Sea surface temperature gradient between the western equatorial Indian Ocean (50˘70° E and 10° S˘10° N) and the southeastern equatorial Indian Ocean (90˘110° E and 10° S˘0° N) (Su et al., 2019). WP constitutes a prominent mode of winter mid-latitude variability, and studies have affirmed that due to its pattern and variability, it strongly influences the hydroclimatology of Canada and the United States (Linkin & Nigam, 2008; Nigam & DeWeaver, 2015).

Despite the existing body of work on teleconnections across the Canadian Shield and the Hudson Bay, very little focused on the hydrology of regional basins; most of the existing studies are on climate extremes (Asong et al., 2018; Dinis et al., 2019; Le Goff et al., 2007; Tan et al., 2016). Different approaches are available to investigate teleconnection's role in river flow, such as sensitivity analysis, probability distribution such as copula, uncertainty analysis, distributed models, scenario, and delta approaches (De Niel et al., 2019; Lenderink et al., 2007; Vansteenkiste et al., 2013). However, this study focuses on sensitivity analysis because it gives relevant information on the magnitude and direction of the effect of teleconnection on river discharge. Sensitivity analysis does not give information about the time and frequency of interaction; hence, wavelet analysis. The periodic nature of river discharge and teleconnection patterns suggests studying them using wavelet coherence in the time and frequency domain.

2 | METHODOLOGY

2.1 | Data and study area

The Humber River Catchments (HRC_{ON} and HRC_{NL}) are presented in Figure 1. At the HRC_{ON}, and the selected stations (02HC009 and 02HC003), a subbasin of the greater Lake Ontario basin, drains an area of about 900 sq. km at the northwest end of the lake and is home to more than 850,000 residents within the Boreal Shield Ecozone (van Lier et al., 2011). In addition, HRC_{ON} is the largest in Toronto and Region Conservation Authority's (TRCA) jurisdiction. With headwaters beginning on the Oak Ridges Moraine, the Humber River exhibits complex erosional histories (Phillips & Robert, 2005). On the other hand, the Humber River Catchment, NL (HRC_{NL}), and its selected station (02YL001) originates from the Gros Morne National Park and drains into the Bay Islands. There are two main branches of the HRC_{NL}; Upper Humber has a drainage area of 2110 km^2, and Grand Lake, which is regulated to produce hydroelectricity at Deer Lake, has a drainage area over 5000 km^2 (Environment and Climate Change, 2024). The Upper Humber River basin near Reidville (02YL001) on the west coast of NL is the second largest river basin on the island, and several communities within the basin are subject to flooding due to extreme events. The catchments provide information on the river's dynamics through a profound understanding of the processes, forms, and feedback that contribute to it, according to a range of temporal and spatial scales.

These three stations (02HC009, 02HC003, and 02YL001) across the two catchments with continuous data between 1970 and 2020 were chosen for this study. The geographical coordinates and characteristics of the stations are shown in Table 1. Daily river discharge data were obtained from the Water Office Canada (https://wateroffice.ec.gc.ca/download/index_e.html?results_type=historical). The data were aggregated to monthly means. Monthly indices for large-scale oscillation were obtained from https://www.esrl.noaa.gov/psd/data/climateindices/ for SOI, TNA, NAO, PNA, and WP, while DMI data were obtained at http://www.jamstec.go.jp/frcgc/research/d1/iod/DATA/. The monthly time series of considered teleconnection indices are presented in Figure 2.

2.2 | Analysis

It is essential to know how one variable (dependent variable) changes with respect to changes in another variable (independent variable). This relationship shows how sensitive the dependent variable is to a one-unit change in the independent variable. We aim to understand how sensitive river discharge in the Humber catchments is to external variables such as large-scale climate oscillations. Correlation and linear regression are two common approaches to observing these changes and their strengths. However, in this study, the sensitivity of river discharge at the stations to the teleconnection indices was investigated using the approach of Ward et al. (2010). It is based on the linear regression equation. The sensitivity of monthly river discharge q_i to a teleconnection index a_i is given by

$$\text{In } q_i = \beta_0 + \beta_1 a_i + \in_i, \tag{1}$$

q_i is the mean monthly discharge, β_1 and β_0 are coefficients of the regression analysis and $_i$ is the error. β_1 represents the sensitivity of river discharge to teleconnection indices (Bouwer et al., 2008). A negative value of β_1 shows that a unit increase in one teleconnection index causes a reduced discharge at a river station. In contrast, a positive value

FIGURE 1 Map showing the three stations and their extent.

causes an increased discharge at the same river. The higher the value, the higher the response of the dependent variable to the independent variable.

Linear regression is based on the statistical properties of the variables involved. However, there is a need for further analysis if the variables involved have periodicity. River discharge and most teleconnection have periodic patterns; hence, linear regression cannot give a complete picture of their relationship. A statistical technique called wavelet coherence examines the relationship between two-time series in frequency and time domains. It is especially helpful when examining the correlation or coherence between two signals that might have different frequencies and/or times. A localized and time-varying measure of the correlation between the signals at various frequencies is given by wavelet coherence. Torrence and Compo (1998) defined the wavelet cross-power between river discharge (X) and teleconnection indices (Y) as:

$$W_n^{XY} = W_n^X(s)\,W_n^{Y}{}^*(s), \tag{2}$$

where * represents the complex conjugate of the signal, $W_n^X(s)$ and $W_n^Y(s)$ are the continuous wavelet transform of X and Y respectively, n is the length of the data, and s is the scale or frequency. It strengthens the coupling between the two signals at different frequencies and time points. High values indicate strong coupling between the two variables. The wavelet coherence is then defined as

$$R_n^2 = \frac{\left|S\left(W_n^{XY}(s)\right)\right|^2}{S\left(\left|W_n^X(s)\right|^2\right)\, S\left(\left|W_n^Y(s)\right|^2\right)}, \tag{3}$$

where $S(\cdot)$ is the smoothing function, W_n^{XY} is defined as the cross-wavelet transform of X and Y. Morlet's wavelet was used to estimate the coherence of this study. Wavelet coherence is a technique used to quantify the relationship or coherence between two-time series as a function of both time and frequency/period (Jiang & Mahadevan, 2011). The coherence values range from 0 to 1, with higher values indicating a stronger correlation or coherence between the two-time series at a particular time and period. To understand the relationship between teleconnection patterns such as ENSO and river discharge, the wavelet coherence plot provides valuable information about the strength and timescales of the coherence between these climate indices and river discharge patterns. Each coherence plot represents the wavelet coherence between a specific teleconnection pattern (e.g., DMI, NAO, PNA, SOI, TNA, and WP) and river discharge data. The horizontal axis represents time (e.g., months or years), while the vertical axis represents the period or frequency (e.g., cycles per year or years per cycle). The colors in the plot indicate the strength of the coherence, with warmer colors (red, yellow) representing high coherence values (close to 1) and cooler colors (blue) representing low coherence values (close to 0). Areas with high coherence (warm colors) suggest a strong correlation between the teleconnection pattern and river discharge at that particular time and period/frequency (Jiang & Mahadevan, 2011; Mullon et al., 2013). By examining the high and low coherence patterns across different timescales and time periods, it is possible to identify the specific timescales and periods when the teleconnection patterns are most strongly correlated with river discharge variability. For example, suppose the SOI panel (representing ENSO) shows high coherence (red areas) at certain periods (e.g., 2–7 years). It may indicate that ENSO cycles at those timescales strongly correlate with river discharge patterns.

TABLE 1 Study area and its attributes.

Characteristics	02HC009	02YL001	02HC003
Station name	East Humber River Near Pine	Upper Humber River Near Reidville	Humber River at Westin
Station code	02HC009	02YL001	02HC003
Latitude	43^o 47"24"N	49^o 14"34"N	43^o 41" 56" N
Longitude	79^o 35' 03" W	57^o 21' 36" W	79^o 31' 13" W
Drainage area (km^2)	19	2,110	802
Mean	1.53	72.78	5.9
Std	1.23	67.66	5.1
Min	0.13	5.91	0.83
25%	0.55	27.41	2.68
50%	1.35	51.94	4.03
75%	2.05	91.99	7.19
max	9.52	383.32	38.04

3 | RESULTS AND DISCUSSION

The monthly time series of the river discharge at each station is shown in Figure 3. Between 1970 and 2020, stations 02HC009 and 02HC003 (HRC_{ON}) present similar trends in river flow, however, with varying magnitude. 02YL001 (HRC_{NL}) presents a different pattern in volume but with similar trends. In the early 1970s and 1990s, the flow records presented the most significant increase in volume; post-1990s, there has been a considerable drop in river flow across the three subbasins (02HC009, 02HC003, and 02YL001). This supports the claim made by the World Wildlife Fund (WWF) Canada in their assessment of Canadian rivers. In their report, WWF-Canada claimed that rivers in Canada are at risk due to declining flow,

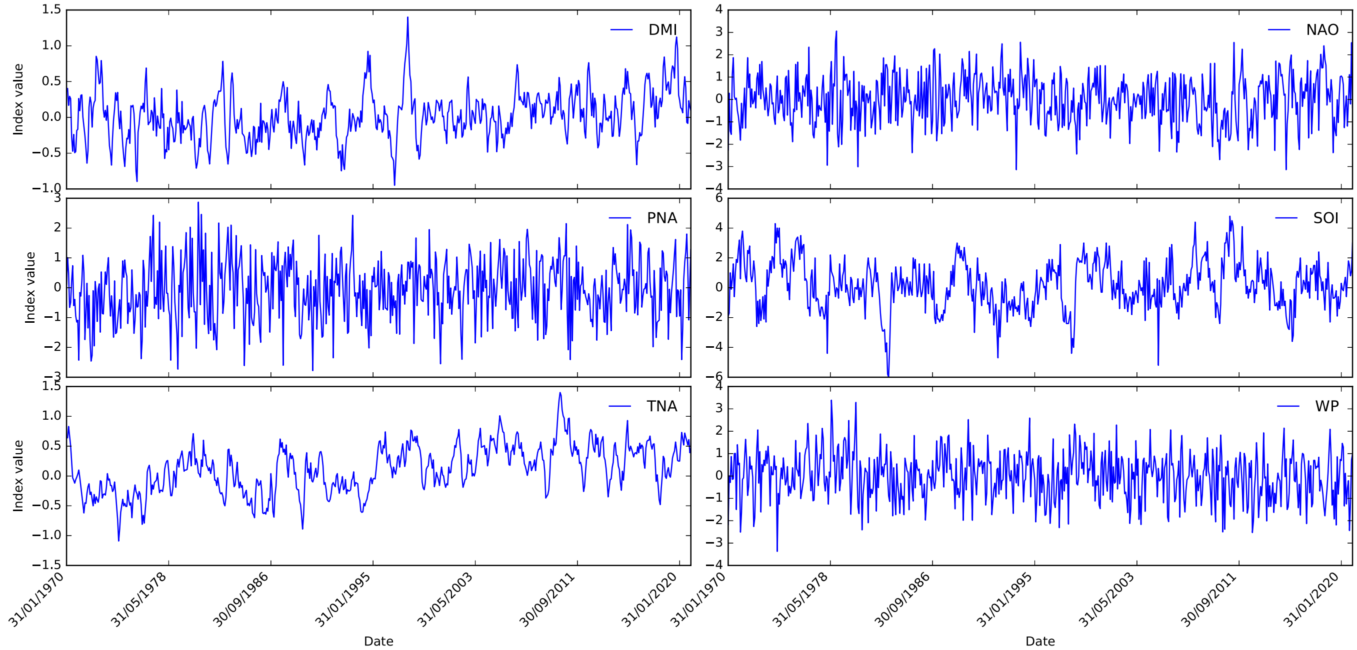

FIGURE 2 Temporal evolution of six climatic indices used in this study.

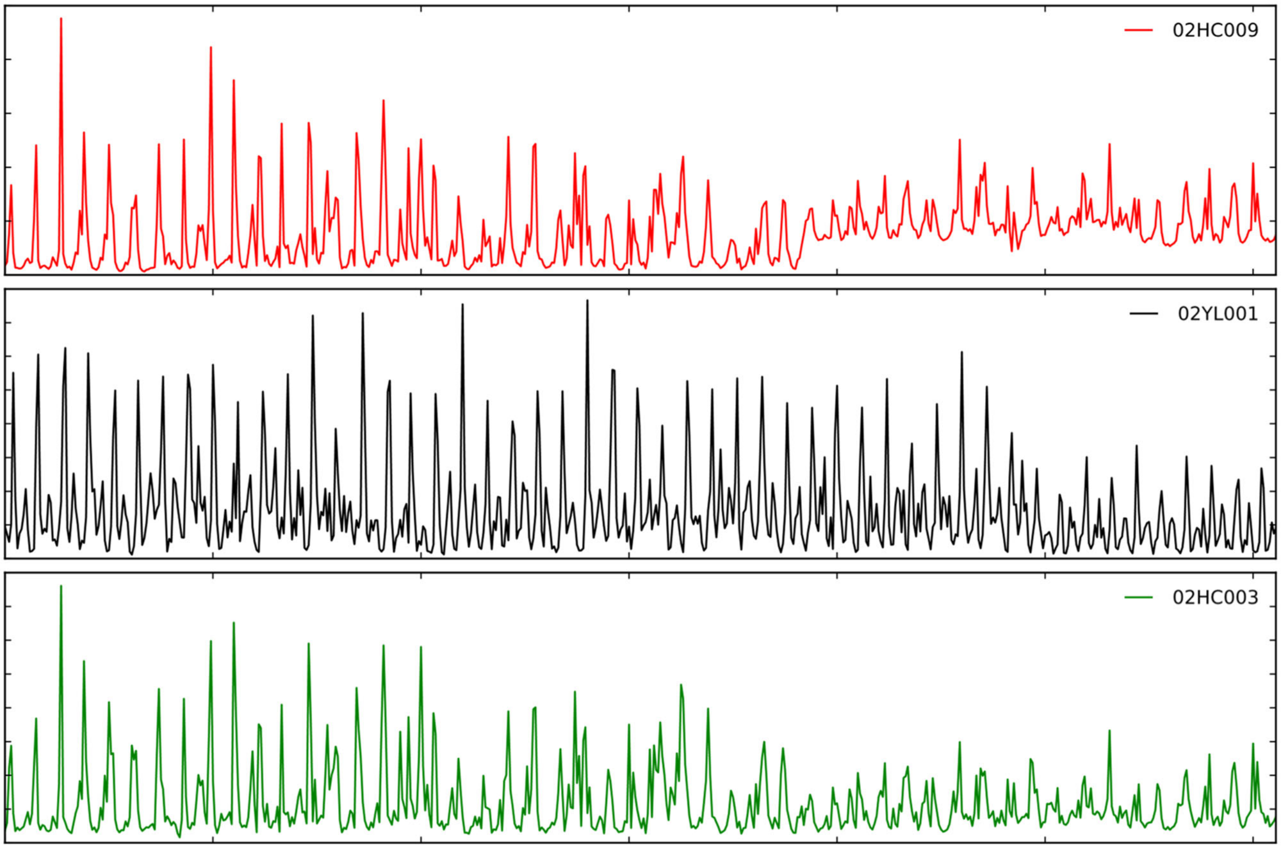

FIGURE 3 Temporal evolution of monthly river discharge at the three locations under consideration.

TABLE 2 Sensitivity analysis of river discharge to teleconnection indices for the period under consideration.

Stations	Station code	DMI	NAO	PNA	SOI	TNA	WP
East Humber River Near Pine ($\mathrm{HRC}_{\mathrm{ON}}$)	02HC009	0.304*	−0.033	−0.02	−0.012	0.394*	−0.052
Upper Humber River Near Reidville ($\mathrm{HRC}_{\mathrm{NL}}$)	02YL001	−0.109	0.041	0.049	−0.003	−0.141	0.075**
Humber River at Westin ($\mathrm{HRC}_{\mathrm{ON}}$)	02HC003	−0.007	0.012	−0.087*	0.003	−0.167**	0.011

*Significant at 99% confidence interval.

**Significant at 95% confidence interval.

flow regulation, and fragmentation by dams, docks, and reservoirs, water withdrawals and diversions, and changing climate. Across these three subbasins, 02HC009, 02HC003, and 02YL001, various anthropogenic activities have been identified as contributors to the declining flow, such as agriculture and dams (Poff & Hart, 2002; St. George, 2007). For instance, Lake Diefenbaker, built during the Gardiner Dam and the Qu'Appelle River construction, is an example of a pronounced reservoir influencing river flow in the region. The unique signature pattern presented by the rising and falling limbs of the river flow across the stations is attributed to reductions experienced during the winter months and the increased recharge and snow-melt during the spring (St. George, 2007). However, the impact of changing climate has been on the rise recently as enabling and compounding the increasing reduction in river flow across the country, including these three stations (Quilbé et al., 2008; Simsarian, 1938; St. George, 2007; Tan & Gan, 2015; Wijesekara et al., 2012; Wolfe et al., 2008). Large-scale climate oscillations influence climate by altering atmospheric circulation patterns, sea surface temperatures, and the distribution of heat and moisture across the globe (Bonsal & Shabbar, 2008). Conversely, the climate can influence the behavior of these oscillations (Maher et al., 2018). Changes in global temperature, driven by factors such as greenhouse gas emissions, can alter the intensity and frequency of climate oscillations. Therefore, based on the sensitivity of river flow to these oscillations Table 2, aside from obvious anthropogenic factors, natural systems such as large-scale oscillations also compound variable flow reduction across these three subbasins.

Table 2 presents an assessment and comparison of the sensitivities between the monthly river flow and the six indices for large-scale climate oscillations. River discharge sensitivity to large-scale climate oscillations was found to vary significantly among the three stations considered. The overall significant large-scale climate oscillations contributing to the river discharge dynamics were DMI and TNA indices for 02HC009, WP index for 02YL001, and PNA and TNA for 02HC003. In January (Figure 4), at 02HC003, in the Humber River at Westin, river discharge has strong positive (0.6) and negative (−0.6) sensitivity to NAO and PNA indices, respectively. It also exhibited relatively strong positive sensitivity to SOI (0.5) in February and May. Between October and December, strong negative sensitivities of −0.8, −0.8, and −0.7 were found between monthly river discharge and SOI at 02HC003. Hence, river discharge at this station during January, February, May, October, November, and December are sensitive to large-scale oscillation indices of NAO, PNA, and SOI. The river discharge sensitivity to the SOI index has the highest magnitude, especially from October to December, due to the SOI index being negative during El Nino and positive during La Nina events. Ward, Eisner, et al. (2014), in their study, observed that between 1958 and 2000, significant impacts of ENSO on annual floods were found in approximately more than 30% of river basins globally. Similarly, Kiladis and Diaz (1989) show that ENSO strongly correlates with precipitation in the boreal autumn across most subtropical and tropical regions. It has also been established that the Arctic oscillations and PNA significantly influence river discharge at different time scales in Yenisei and Ob' rivers (Zhang et al., 2023). In addition, Dipole Mode Index and Southern Oscillation index contribute about 8–41% and 0.4–2.5% to the annual river discharge in the Niger basin, respectively (Ogunjo & Olusola, 2022).

The variability in the sensitivity of the river flow at 02HC003 to NAO could be partly explained using these three indices (NAO, PNA, and SOI) during the corresponding months for the months ahead. For instance, Munoz and Dee (2017) found that the influence of El-Nino on flood events leading to precipitation anomaly at the lower Mississippi basins could be detected up to 6–12 months ahead. However, this study precludes the river discharge estimation using large-scale oscillation indices. The overall results for 02HC003 show that the river discharge's sensitivity to PNA and TNA indices is more pronounced for the entire consideration period. At 02YL001, in the Upper Humber River Near Reidville, river discharge in April is highly positively sensitive (0.6) to PNA and WP indices. Similar connections have been observed between PNA and rivers flowing within Labrador and the Hudson Bay (Déry & Wood, 2004). Although the method of analysis in their study was based on correlation, positive teleconnections were confirmed between rivers flowing within these areas and PNA. Déry and Wood (2004) showed that the Arctic Oscillation explains the recent variability in Hudson Bay River discharge with a correlation value of −0.88. In May, the sensitivity for NAO and PNA is demonstrated with positive

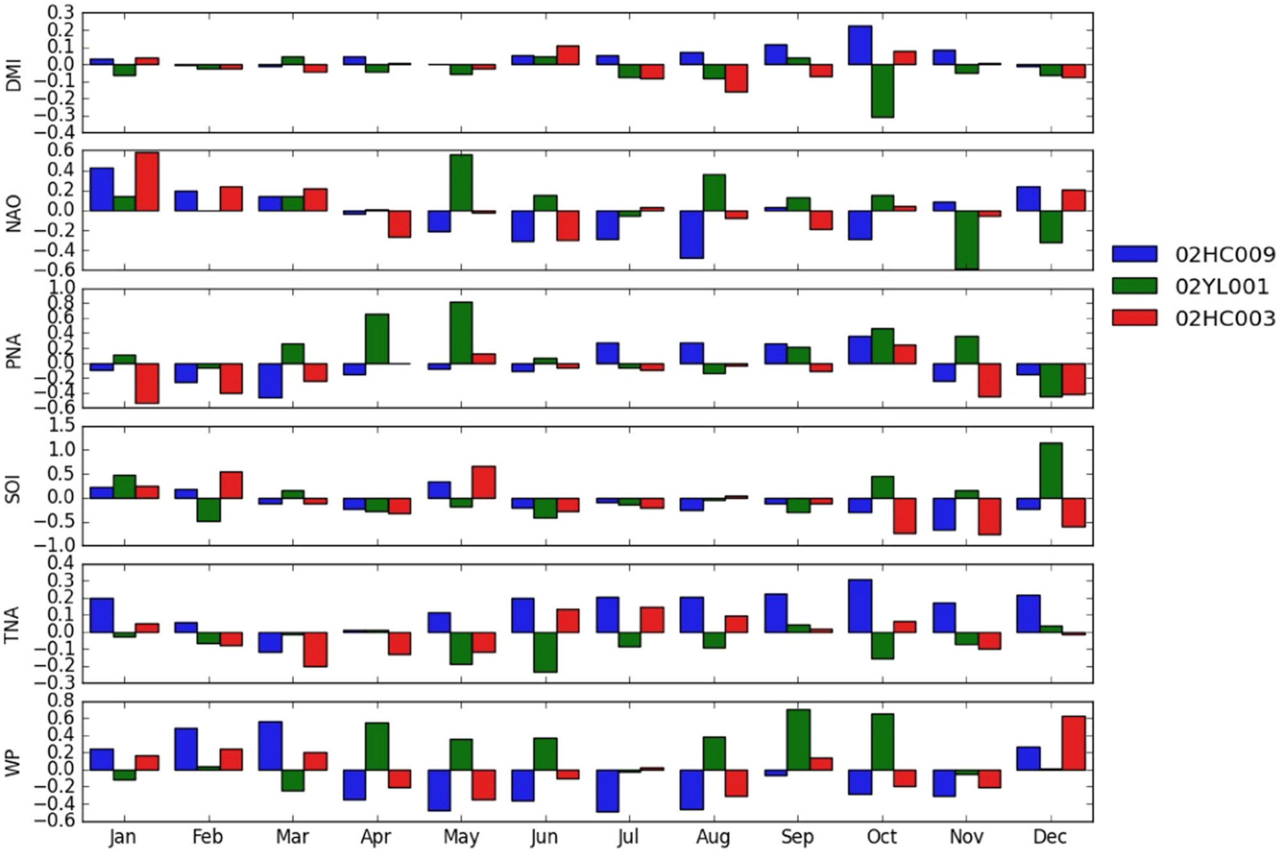

FIGURE 4 Monthly sensitivity analysis of river discharge at the three locations to each of the six climatic indices.

values of 0.6 and 0.8, respectively. Similarly, in September, the river discharge was positively sensitive (0.6) to WP, which persisted until October. In November and December, the river discharge exhibited strong negative sensitivity to NAO (−0.6) and positive sensitivity (1.0) to SOI. The statistical tests for significance (Table 2) show that the river discharge sensitivity to the WP index is significant. For example, at 02HC009, in the East Humber River Near Pine, river discharge was sensitive to WP in March with a magnitude of 0.5. Meanwhile, negative sensitivity values of −0.5 are found during May, July, and August. Generally, this station is not very sensitive to the large-scale oscillations investigated. In addition, during December, the correlation of monthly river discharge with the WP index is reasonably strong. Generally, an attempt to detect the possibility of impacts or influence of large-scale climate oscillations on monthly river discharge at the three sites has revealed the likelihood of such effects as they vary monthly. The overall findings from the sensitivity analysis, which will change with time, suggest that large-scale climate oscillations pose added risks to the variability of river discharge at the three stations. This will align with possible changes in the teleconnection strengths due to climate change Emerton et al. (2017); Ward, Jongman, et al. (2014). Generally, the inland stations have a similar direction of sensitivities to these (02HC009 and 02HC003), which differs from the coastal station (02YL001). The sensitivity patterns observed between inland (HRC_{ON}) and coastal (HRC_{NL}) stations suggest that the influence of large-scale oscillations on river flow varies by region. While inland stations exhibit similar sensitivity patterns, the coastal station demonstrates unique responses, likely due to differences in local climate dynamics, land surface characteristics, and proximity to marine influences. These regional differences emphasize the importance of considering local context when evaluating the impact of large-scale oscillations on river systems (Vu et al., 2023).

The observation in Figure 5 presents the dynamics of these oscillations with respect to time. Even though some of the observed dynamics were not continuous, inferences can be made about how these oscillations perform across the subbasins. At East Humber River near Pine (02HC009), the

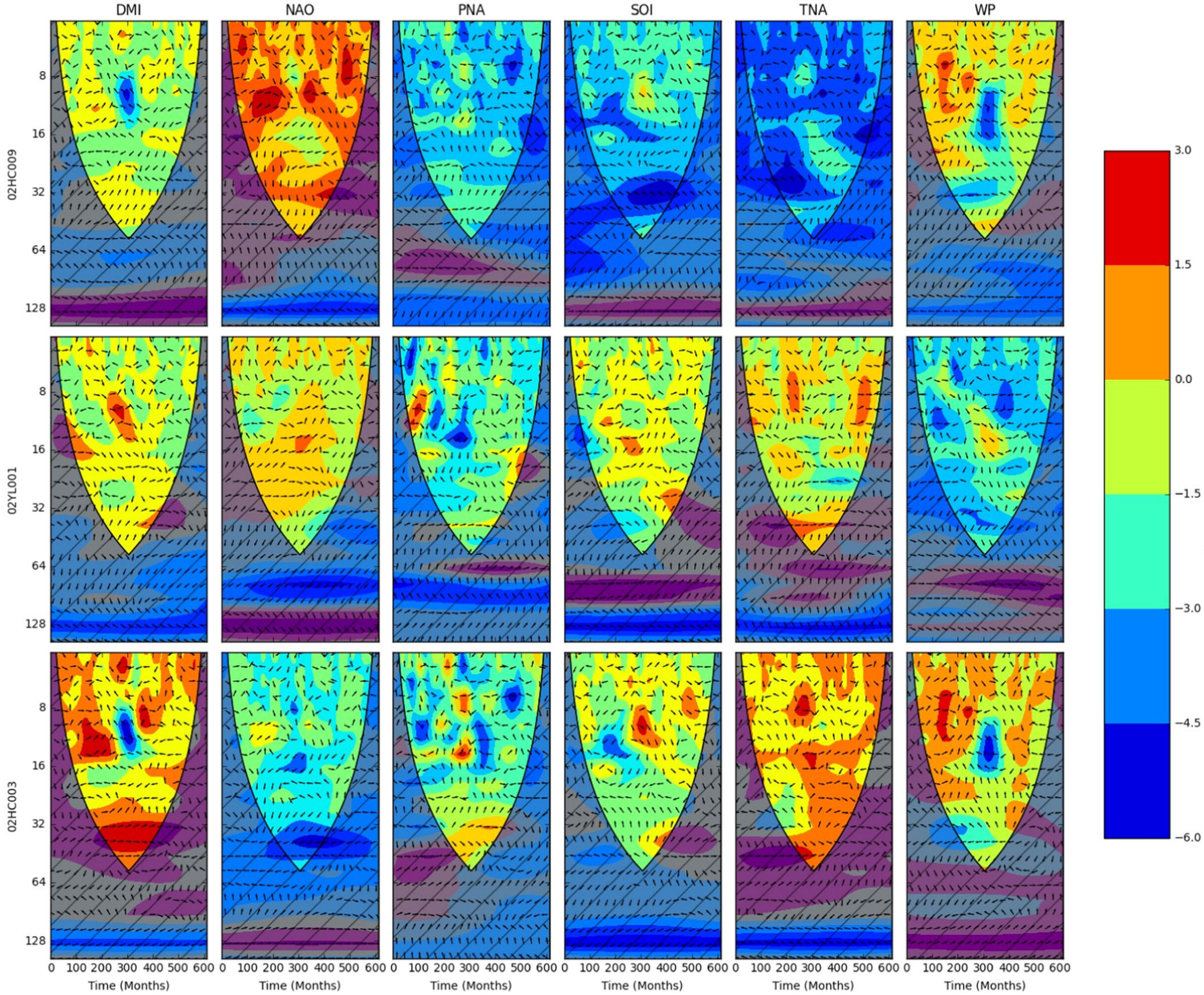

FIGURE 5 Cross power between the river discharge at the three locations and six climatic indices.

temporal variations in NAO and river flow fluctuations can be seen. The high-power regions fluctuate on interdecadal timescales. From the 1970s−1980s and 1990s−2000s, intense interdecadal changes in the 8-to-16-year power were observed. The observed temporal variations in NAO and river flow at East Humber River near Pine signify a dynamic interplay between atmospheric and hydrological processes. This has implications for local water resource planning, as understanding these variations is crucial for managing water availability and mitigating potential impacts on ecosystems and communities. The agreement with NAO aligns with other studies highlighting the climatic teleconnection between northeastern and northwestern Atlantic seaboards with NAO (Bonsal & Shabbar, 2008; Bouwer et al., 2008; Kingston et al., 2006). This is, however, different for other locations. Identifying noncontinuous dynamics in large-scale oscillations across subbasins suggests a nuanced and potentially complex behavior. This variability could affect water resource management, ecosystem dynamics, or climate modeling, highlighting the need for detailed and site-specific analyses. In contrast, other large-scale climate oscillations have little power or show significant agreement with river flow. During the 1970s–1980s and 1990s–2000s, the 8-to-16-year power was significantly above the 95% confidence for red noise. This implies that 5% of the wavelet power should be above this level. For the Upper Humber River near Reidville (02YL001), these oscillations present very little forcing on the river flow at this station, with no significant association observed. This could be due to local hydrological characteristics, and understanding this interaction becomes essential for accurate water management strategies. However, at the Humber River at Weston (02HC003), temporal variations between DMI, TNA, and WP can be seen. The high power regions fluctuate on an (inter)decadal timescale for DMI, TNA, and WP. Specifically, from the 1980s to the 1990s, strong decadal fluctuations in the 8-to-32-year power were observed for DMI (Figure 6).

Identifying temporal variations between DMI, TNA, and WP at this location implies a more complex

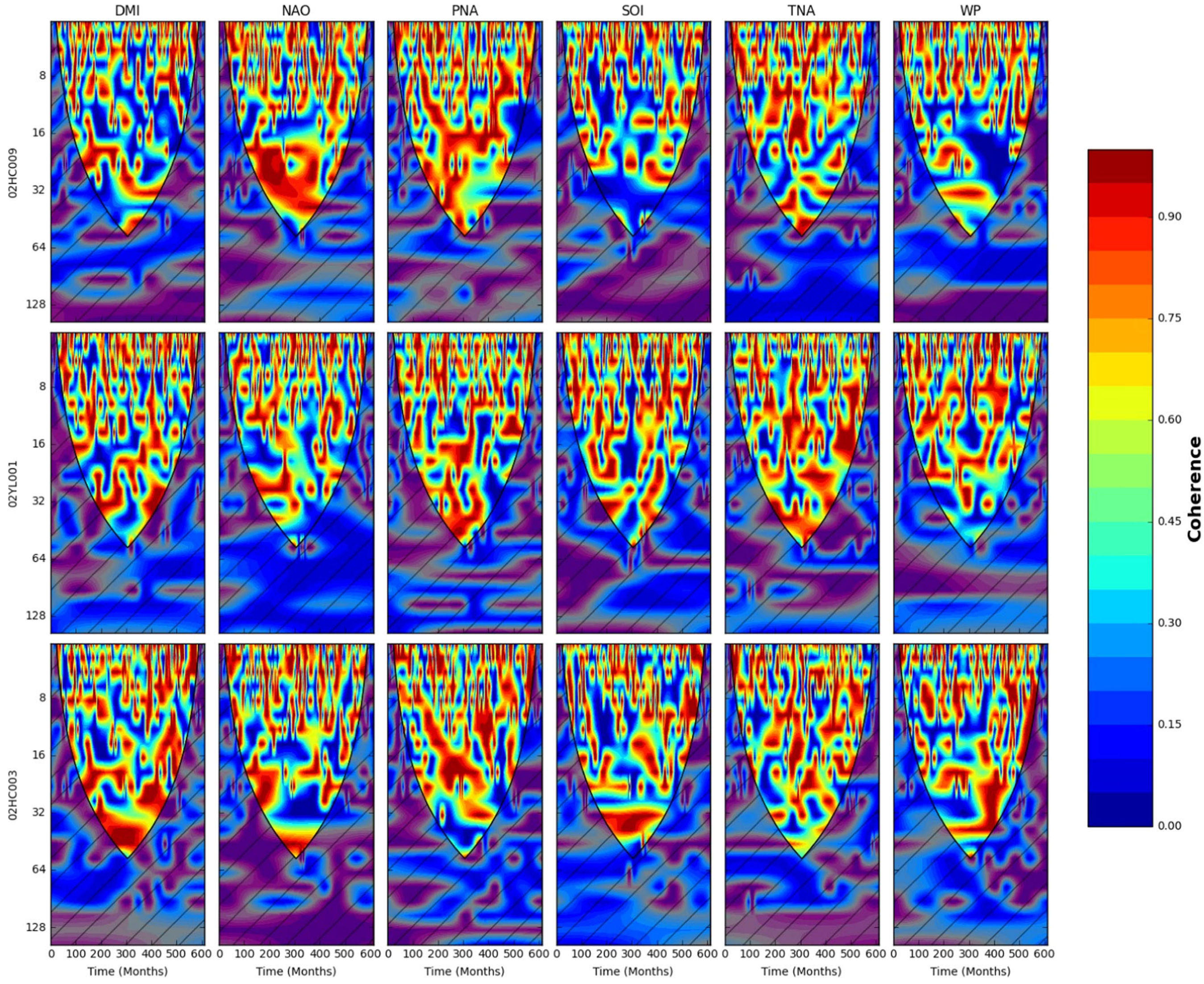

FIGURE 6 Wavelet coherence between the river discharge at the three locations and six climatic indices.

relationship between climatic indices and river flow dynamics. The observed (inter)decadal fluctuations in the 8-to-32-year power for DMI during the 1980s to the 1990s highlight the need to understand climate variability's impact on water resources over different time scales.

In contrast, between the 2000s and 2010s, strong decadal observations were observed for TNA between the 1970s and 1990s, and strong interdecadal fluctuations were observed for WP. This temporal variability suggests dynamic changes in the climatic indices over these periods. The wavelet coefficients from the analysis across the three subbasins are shown. Statistically, significant wavelet power with respect to timefrequency is shown with thick lines in a conical form 6. Significant active multidecadal oscillations were observed for only NAO with high power within East Humber River Near Pine (02HC009, Red), while others were low in power. The observation of significant multidecadal oscillations for NAO within East Humber River Near Pine (02HC009) suggests NAO's prolonged and impactful influence on the climatic conditions in that specific location. However, at Humber River at Westin (02HC003), DMI showed high power for three decades, indicating a sustained climatic impact on this location. Understanding the variations in climatic indices is crucial, especially considering the potential implications for water resource management and ecological resilience. The presented patterns were relatively low for other periods and locations across the studied subbasins. Knowing if the observation is spurious or just coincidence becomes challenging. As pointed out by Grinsted et al. (2004), the cross-wavelet transform could help judge similarities empirically.

These observed fluctuations gain significance in the broader context of a changing climate. Climate change in the North American region is of global interest. There have been reports of increasing ice melt in the North American region (Wu & Li, 2022). This can alter the amount of precipitation in different regions of the continent. Changes in precipitation affect river discharge since it is our rivers' primary water source. An increase in sea surface temperature, especially around ENSO, has also been reported in literature (Cai et al., 2021). ENSO also strongly influences precipitation, not only on the North American continent but worldwide and other teleconnection patterns (Ogunjo & Fuwape, 2020). Changes in ice melt, teleconnection patterns and other environmental factors will directly impact river discharge in the near future. In ON and NL, regions with unique geographical and climatic characteristics, understanding the intricate relationships between climatic indices and river flow is imperative. The implications extend to water resource management, as variations in river flow can impact ecosystems, agriculture, and communities. Adapting to these changes becomes crucial, emphasizing the need for dynamic and resilient strategies in the face of evolving climatic patterns. The potential mechanism by which these large-scale oscillations impact river flow in Canada include changes in precipitation patterns (Cai et al., 2021), temperature anomalies caused by teleconnection patterns (Wallace & Gutzler, 1981), atmospheric circulation, and hydro-climatic complexities associated with individual watersheds (Bonsal & Shabbar, 2008).

4 | CONCLUSION

The ability to successfully manage water resources rests on successfully monitoring river flow. River flow is essential in basin management, and a careful monitoring program ensures adequate water and resources are provided. In this study, we have highlighted the gradual decrease in river flow across the three stations within the Humber Catchments (HRC_{ON} and HRC_{NL}) between 1970 and 2020. Irrespective of their locale, river flow across these stations has declined post-1990s due to various factors such as land use-land cover, water management and practices, dam and bridge construction activities, and external factors like climatic indices. In light of the changing climate, a persistent reduction in river flow will have a cascading effect on other aspects of the basin, affecting the provision of essential ecosystem services. Based on the aforementioned and the significant interdecadal changes in power observed in this study, particularly during the 1970s–1980s and 1990s–2000s, underscore the long-term variability in the system. Such fluctuations may have implications for infrastructure planning, as they could impact the reliability and sustainability of water-related projects over extended periods.

Second, as pointed out in this study, an assessment of the contributions and impact of large-scale climate oscillations on the river flow at the three locations considered using sensitivity and wavelet analysis showed the effect of these oscillations on the seasonal variation of river flows. Specifically, at the Humber Station (HRC_{NL}), the correlation of monthly river flow with the WP index is pretty strong in December. However, an attempt to detect the possibility of impacts or influence of these oscillations on monthly river discharge at the three sites reveals a monthly variation. The sensitivity analysis findings suggest that large-scale climate oscillations pose added risks to river flow variability at the three stations. This is expected to align with the possibility of changes in the teleconnection strengths due to climate change. We affirmed that stations within Humber (HRC_{ON}) have a similar direction of sensitivities to the large-scale climate oscillations, which differs from those along the coast. The observed inconsistency in the relationship between the oscillations and, for example, NAO at various locations suggests that the impacts of climate oscillations may manifest differently in different regions. This spatial variability underscores the importance of localized studies and adaptive management strategies tailored to each area's specific climatic and hydrological conditions.

Third, different phases of climate oscillations are more significant within the subbasins draining HRC_{ON}. Specifically, climatic indices such as DMI, NAO, WP, and TNA leave a more distinct imprint on the river flow patterns within these subbasins than those along the coast. Notably, the strength of observed decadal cross-power associations within the coastal basin appears less robust than the compelling relationships found within the subbasins in HRC_{ON}. The observed regional variation underscores the complexity of climatic influences on river flow and prompts further inquiry into the dynamics of these relationships. As such, there is a need for additional studies to adequately understand the interplay between large-scale oscillations and river flow across Canada. Expanding the scope to include more subbasins, encompassing diverse geographical and climatic contexts, will provide a holistic perspective on the dynamics and interrelationships between climatic indices and river flow patterns. In addition, this study lays the groundwork for future research endeavors, promising to enhance river flow forecasting. In an era of changing climate, where uncertainties loom over hydrological patterns, the insights gained from this study contribute valuable information for careful planning and sustainable water resource management. By advancing our understanding of how climatic indices influence river flow, this research is a crucial building block in developing proactive strategies that mitigate the impacts of a changing climate on water resources.

DATA AVAILABILITY STATEMENT

All data used in this study are publicly available and stated in the manuscript

ETHICS STATEMENT

None declared.

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