Water Quality Research Journal

Water Quality Research Journal Vol 60 No 2, 348 doi: 10.2166/wqrj.2025.053

Compound thermal indices for two species of salmonids

Habiba Ferchichi [a,b,*], André St-Hilaire [a,b], Jean-Nicolas Bujold[c], Alexandra Kassatly[c] and Julie Vajou[a]

[a] Centre Eau Terre Environnement, Institut National de la Recherche Scientifique, 490 de le Couronne St., Québec City, QC G1K 9A9, Canada
[b] Canadian Rivers Institute, University of New Brunswick, Fredericton, NB, Canada
[c] Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs, 880 chemin Ste-Foy, Québec City, QC G1S4X4, Canada
*Corresponding author. E-mail: habiba.ferchichi@inrs.ca

HF, 0000-0001-5175-9189; AS, 0000-0001-9161-4742

ABSTRACT

Water temperature is a determinant variable for the overall health of the river ecosystem and aquatic biota, particularly for cold-water fish. Therefore, the characterization of river temperature is essential for the management of thermal habitats. However, currently, river thermal regime characterization is often achieved by calculating numerous thermal indices that are not often related to cold-water fish physiological requirements and thermal preferences. In this study, we developed a compound thermal index (CTI) based on a methodology used to calculate the water quality index (WQI) in Canada. CTI is composed of specific indicators related to the thermal tolerance thresholds for different life stages for two cold-water species (Atlantic salmon and brook trout), providing a simplified measure of the quality of the thermal habitat for these species. CTI was determined in two salmon/trout rivers in Québec, Canada (Ouelle and Ste-Marguerite). The results showed that (i) CTI allowed the characterization and classification of thermal habitat quality; (ii) the thermal habitat degradation was primarily influenced by climate conditions, particularly during warm and dry years with high temperatures and low precipitations; (iii) the improved thermal habitat quality was associated with air temperature and precipitation values close to seasonal normals; (iv) cold tributaries provided excellent thermal habitats.

Key words: compound index, fish habitat quality, river temperature, thermal index, thermal habitat index, water quality index

HIGHLIGHTS

- The compound thermal index (CTI) is a simple and easily interpretable indicator of thermal habitat quality for cold-water species.
- CTI temporal variation showed that the degradation of the thermal habitat occurred mostly during the warm and dry years and was mostly affected by climate conditions.
- CTI spatial analysis revealed that many cold tributaries provided excellent thermal habitats for the cold-water species.

INTRODUCTION

The characterization of river temperature is a complex multivariate problem since it includes several factors related to atmospheric meteorological properties (extreme air temperatures and solar radiation, etc.), hydrological conditions (low water flow and groundwater input, etc.), and ecological functions (exceeding thermal tolerance thresholds for aquatic species, etc.). This characterization is often achieved by calculating one or more thermal indices, i.e., descriptive statistics calculated from temperature time series. The most basic indices relate to extremes (minimum and maximum) and central tendency (mean or median). More sophisticated indices have been used for river thermal regime classification in rivers. Thermal sensitivity, which is the slope of the air–water temperature regression line for a given river site, is an index that has been commonly used in recent years (Chang & Psaris 2013; Leach & Dan Moore 2019; Boyer *et al.* 2021).

Maheu *et al.* (2016) fitted a sinusoidal function to annual river temperature time series. Using the amplitude and phase of the function, they were able to classify 135 US rivers in six categories. Daigle *et al.* (2019) proposed to use three parameters of a Gaussian function fitted to interannual daily mean time series to characterize the thermal regime of Québec (Canada) rivers. One parameter was indicative of the maximum amplitude of the function, one was associated with the timing of that maximum value and one indicated the length of the warm-water period. The three parameters were mapped for all Québec rivers with temperature gauges and time series greater than 5 years. The same three parameters were used by Abidi *et al.* (2022), in addition to maximum temperature and the number of days with temperature >25 °C to characterize the thermal regime of over 100 Eastern Canadian rivers. They also developed methods to estimate these indices at ungauged sites. Beaufort *et al.* (2021) defined the thermal peak as a relatively simple thermal metric to be applied at the regional scale. It is defined as the interannual mean of the 30 days with the highest temperature.

All of the aforementioned indices aim at providing a general classification of river thermal regimes. However, in some cases, indices need to be selected for management purposes. One of the most common cases is the definition of thermal thresholds for fisheries management and fisheries closure. For instance, some river systems in Eastern Canada that have an Atlantic salmon (*Salmo salar*) population subjected to angling are managed using temperature thresholds (e.g., angling is closed when day-night water temperatures are greater than 20 °C; Van Leeuwen *et al.* (2023)). In most cases, the selected index relates to the tolerance of one life stage. For many species, thermal stress is induced at different temperature thresholds for different life stages. As an example, Oyinlola *et al.* (2023) listed the different sub-optimal and critical thermal thresholds for three early life stages of white sturgeon (*Acipenser transmontanus*): embryo, yolk-sack larvae, and juvenile. Hence, it can readily be seen that even for one species, multiple thermal indices are required to fully characterize the adequacy between the species requirements and the river thermal regime.

Similar problems have been encountered in other contexts and were addressed by using a compound index approach. The compound index is a general indicator composed of a set of specific individual indicators by providing a simplified measure that summarizes their quality or performance. In fish ecology, the approach was popularized by the seminal work of Karr *et al.* (1986), who proposed a methodology for the development of an Index of Biological Integrity for rivers. They sampled fish assemblages from which they computed metrics related to abundance, species diversity, and trophic levels. The multiple indices were combined in a compound index made comparable for one river to the other. The same approach is used by many jurisdictions for water quality. For example, the water quality index (WQI) of the CCME (Canadian Council of Ministers of the Environment 2001) synthesizes water quality information and facilitates its explanation and presentation to managers and the general public. Indeed, the CCME WQI mathematically combines several variables describing water quality (dissolved oxygen, pH, total phosphorus, temperature, etc.) and simplifies the assessment of water quality. Its temporal evolution and spatial variability can be compared to standards and guidelines (Canadian Council of Ministers of the Environment 2001). This index has been adopted since 2001 and applied in water quality monitoring across Canada and around the world, including as an index of drinking water quality and surface water quality (lakes, rivers, etc.). The WQI had been adapted in multiple studies including the water quality assessment of drainage water and watercourses downstream of peat harvesting operations (Betis *et al.* 2020). Peat harvesting may affect the quality of drainage water from peatlands, which is discharged into nearby watercourses. This drained water may alter the water quality in the watercourses and, as a result, impact the habitat of aquatic species. After selecting the adequate physico-chemical parameters that may be affected by peat harvesting (pH, ammonia, conductivity, etc.), the WQI was determined for the harvested peatland and for other streams for comparison (Betis *et al.* 2020). Betis *et al.* (2020) showed a significant difference between the WQI in natural streams and those of the harvested peatlands, indicating that some water quality (e.g., pH) guidelines were not respected in some harvested peatlands.

In the present study, the WQI approach has been adapted to develop compound thermal indices (CTIs) that include thermal tolerance for different life stages of two important fish species in Eastern Canada: Atlantic salmon and brook trout (*Salvelinus fontinalis*). The index was then applied to two important salmon rivers, located in Eastern Canada, where the two species co-exist: the Ouelle River (warm system) and the Ste-Marguerite River (colder system). These two species are exposed to a varying gradient of thermal stress during the summer period (Daigle *et al.* 2015). The salmonid population is exposed to minimal thermal stress in the Ste-Marguerite River, whereas the water temperature in the Ouelle River frequently exceeds the lethal limit temperature for Atlantic Salmon (>28 °C), leading to critical thermal conditions (Daigle *et al.* 2015). These authors showed that the quality of thermal refugia, a cold-water patch used by poikilotherms, in salmon rivers (Ouelle, Ste-Marguerite, and Little Southwest Miramichi) is expected to decrease based on statistical water temperature prediction using 10 different climate scenarios. Indeed, the occurrence and duration of high-temperature events (24 and 28 °C) in the mainstem of these rivers are expected to increase, resulting in a higher need for thermal refugia for the salmonid population (Daigle *et al.* 2015).

METHODS

Thermal tolerances for Atlantic salmon and brook trout

The adaptation of the CCME WQI consists of using the thermal tolerance thresholds in computing the CTI, instead of water quality parameters, for the assessment of the habitat's thermal quality. These thermal thresholds were determined based on a literature review. Tables 1–3 present the definitions and the values of the selected thermal tolerance thresholds for different life stages of Atlantic salmon and brook trout.

Computation of the CTI

After selecting and measuring water quality parameters, the calculation of the CCME WQI is based on the combination of three factors describing water quality: (i) extent, which represents the number of variables or indices that did not meet the recommended water quality criteria; (ii) frequency, which is the number of times these parameters did not conform to the recommended values; and (iii) amplitude, which is the deviation of the non-conforming parameters from the recommended

Table 1 | The definition of the selected metrics for computing CTI in the case of brook trout

Biological category	Metric	Definition	Description
Survival	UILT	Upper incipient lethal temperature	Temperature at which 50% of the population survives an indefinitely long exposure
Growth	OGT	Optimal growth temperature	Temperature that supports the highest individual growth rate in the absence of the confounding factors
	NGT	Negative growth temperature	Temperature at which growth significantly declines or ceases and becomes negative
Reproduction	UST	Upper spawning temperature	Maximum temperature for spawning (eggs become non-viable)

Table 2 | The values of the selected metrics for computing CTI in the case of brook trout

Scientific name	Common name	Life stage	UILT (°C)	OGT	NGT	UST	Reference
Salvelinus fontinalis	Brook trout	Juvenile	26	16	22	–	• UILT : (Brett 1944, Grande & Andersen 1991) • OGT : (Chadwick & McCormick 2017, Graham 1949, Hokanson *et al.* 1973) • NGT : (Chadwick & McCormick 2017)
Salvelinus fontinalis	Brook trout	Adult	24	18	20	16	• UILT: (Kilgour McCauley & Kwain 1985) • OGT: (Ouellet & Daniels 2021) • NGT: (Robinson *et al.* 2010) • UST: (Hokanson *et al.* 1973)

Table 3 | The selected metrics for computing CTI in the case of Atlantic salmon

Thermal thresholds	Temperature (°C)	Reference
Thermal stress for adult	23	Wilkie *et al.* (1997), Breau (2013)
UILT for adult	27.8	Jonsson & Jonsson (2009)
Thermal stress for smolt	25	Elliott (1991), Wilbur *et al.* (2020)
UILT for smolt	25.5	Elliott (1991)
Thermal stress for parr	25	Wilbur *et al.* (2020); DFO (2012)
UILT for parr	26,5	Elliott & Elliott (2010))
UILT for alevins	27,6	Breau (2013), Elliott (1991)
UILT for eggs	16	Smalås *et al.* (2023), Elliott (1981), Elliott & Elliott (2010)

values. From these factors, the index produces a simple value ranging from 0 (worst quality) to 100 (best quality). For the CTI, we use the thermal quality criteria related to the temperature thresholds for different life stages of the targeted cold-water species. According to the Canadian Council of Ministers of the Environment (2017), the index is calculated as follows:

1) Specify the mass of water to be studied (lake, river section, etc.) which can be defined by one or more stations. The number of stations to be included depends on the type of water mass. For example, it is recommended to include a greater number of stations in a river than in a lake in order to capture natural variability.
2) Define the period of the study, which may vary depending on the availability of data and the requirements of the study.
3) Select a minimum of 4 and a maximum of 20 water quality parameters (temperature metrics in the present study) appropriate to the study area and, in our case, fish species.
4) Specify the recommended values for the selected parameters.
5) Calculate the three factors that make up the WQI: extent (F_1), frequency (F_2), and amplitude (F_3):

F_1 (extent) is the percentage of measured parameters that do not conform to the recommended values out of the total number of parameters measured:

$$F_1(\%) = \left(\frac{\text{Number of variables with values outside the recommended range}}{\text{Total number of parameters}}\right) \times 100 \tag{1}$$

F_2 (frequency) represents the percentage of measurements that did not meet the recommended values ('non-compliant results') out of the total number of measurements:

$$F_2(\%) = \left(\frac{\text{Number of samples that do not meet the guidelines}}{\text{Total number of samples}}\right) \times 100 \tag{2}$$

F_3 (amplitude) represents the deviation between the non-conforming measurements and the corresponding guideline values. F_3 is calculated in three steps:

1) *Calculation of the coefficient of deviation*: This represents the amplitude for which an individual measurement (i) of a parameter is higher than its recommended value (or lower, when the recommended value is a minimum):

For values exceeding the guideline:

$$\text{CD}_i = \left(\frac{\text{Measured value}_i}{\text{Recommended value}}\right) - 1 \tag{3}$$

For values lower than a recommended minimum:

$$\text{CD}_i = \left(\frac{\text{Recommended value}}{\text{Measured value}_i}\right) - 1 \tag{4}$$

2) *Calculation of the normalized sum of deviation factors* (*NSDF*): This represents the overall degree of non-compliance, calculated by dividing the sum of the deviation coefficients of all non-conforming measurements of all parameters (n) by the total number of measurements performed (compliant and non-compliant):

$$\text{NSDF} = \left(\frac{\sum_{i=1}^{n} \text{CD}_i}{\text{Total number of samples}}\right) \tag{5}$$

3) *Calculation of the F_3 factor* (*amplitude*): This is calculated as a function of NSDF using an asymptotic function that tends to a fine value in the same range of the other factors, which is between 0 and 100:

$$F_3 = \left(\frac{\text{NSDF}}{0.01 \times \text{NSDF} + \text{NSDF}}\right) \tag{6}$$

4) *Calculate the CCME WQI*: This is calculated as a vector sum of the three factors (extent, frequency, and amplitude) in three-dimensional space. Dividing by (1.732) normalizes the index values within a range of 0–100.

$$\mathrm{WQI} = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right) \tag{7}$$

After computing the CCME WQI values, the water quality is ranked into the following categories (Tables 4):

The adaptation of CCME WQI to characterize the quality of the thermal habitat involves considering different variables or metrics related to the thermal tolerance thresholds of selected species for different life stages (Tables 2 and 3) and computing the CTI. Given that the thermal metrics cover different biological stages occurring at different times of the year, the specific time period covering the reproduction stage (eggs and alevins) was set for salmon (April–May), related to the metrics of UILT for alevins and eggs. For the brook trout, the reproduction period was fixed between mid-September and the end of November (Jean-Bujold & Vachon 2016) associated with the UST metric. For the rest of the metrics, in relation to the growth and survival stages, the time period was fixed from June to October.

For each station on the river (i.e., site) and each year of available daily temperature, the CTI for these species is calculated by combining the three factors (extent, frequency, and amplitude) describing the quality of the thermal habitat. The CTI produces a single value between 0 (worst thermal habitat quality) and 100 (best thermal habitat quality) for each year. The CTI values are classified into five categories of thermal habitat quality (Tables 5), inspired by the classes of the CCME WQI index (Canadian Council of Ministers of the Environment 2001).

Given that the CTI is computed based on the available daily water temperatures at the stations, which vary from one station to another, we established a data quality indicator based on data availability: poor (<50% of the data), good (50–80%), and excellent (>80%).

Table 4 | CCME WQI classes (Canadian Council of Ministers of the Environment 2001)

Classes	CCME WQI ranges	Water quality description
Excellent	95–100	*'water quality is protected with a virtual absence of threat or impairment; conditions very close to natural or pristine levels.'*
Good	80–94	*'water quality is protected with only a minor degree of threat or impairment; conditions rarely depart from natural or desirable levels.'*
Fair	65–79	*'water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels.'*
Marginal	45–64	*'water quality is frequently threatened or impaired; conditions often depart from natural or desirable levels.'*
Poor	0–44	*'water quality is almost always threatened or impaired; conditions usually depart from natural or desirable levels.'*

Table 5 | CTI classes for the quality of the thermal habitat

Classes	CTI ranges	Habitat thermal quality
Excellent	95–100	The quality of the thermal habitat is preserved.
Good	80–94	The quality of the thermal habitat is preserved, with only minor threats or deterioration observed.
Fair	65–79	The quality of the thermal habitat is generally preserved, but it is occasionally threatened or deteriorated; conditions sometimes deviate from desirable levels.
Marginal	45–64	The quality of the thermal habitat is frequently threatened or deteriorated; conditions often deviate from desirable levels.
Poor	0–44	The quality of the thermal habitat is almost always threatened or deteriorated.

Climate classes

River temperature is highly impacted by meteorological conditions. For comparison purposes between years or between regions, it was necessary to associate climate classes with the values of CTI to analyze the impact of air temperatures and precipitations on the CTI variation. Boyer *et al.* (2021) recommended that climate contextualization should be considered in the comparison of the thermal sensitivity of Québec rivers, i.e., the slope between water and air temperatures, given that the rivers are distributed across different climate regions with varying ranges of air temperatures and precipitations that could affect the thermal sensitivity comparisons. The authors defined nine climate classes derived from the combinations of air temperatures (cold, normal, and warm) and precipitation conditions (dry, normal, and wet). This climate contextualization is based on computing the anomalies in maximum air temperature (ΔT_{airmax}) and total precipitation (P_{tot}).

In this study, we applied the same methodology using the daily climate data (ΔT_{airmax} and P_{tot}) from the ERA5 reanalysis grid interpolated on a 30×30 km grid available from 1979 to 2020, in addition to the daily water temperature from Rivtemp (www.rivtemp.ca) and Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs databases, from over 69 watersheds in Québec. Table 6 represents the results of the climate classification. Then, the climate classes of the Ouelle and Ste-Marguerite rivers for each station and year of data were determined.

Case studies

This study showed an application of the CTI on two salmon rivers in the Province of Québec, Canada: the Ste-Marguerite and Ouelle rivers. The Ste-Marguerite River, with a drainage area of 2,100 km^2, is situated in Québec's North Shore region, located on the northern shore of the St. Lawrence River in eastern Québec (Figure 1). The river flows through two main segments: the mainstem (1,120 km^2) and the Northeast tributary (980 km^2). The river ultimately flows into the Saguenay River, near its confluence zone with the St. Lawrence River (Figure 1). The Ouelle River (845 km^2) is located on the south shore of the St. Lawrence River and discharges into the latter approximately 120 km east of Québec City. This river is considered one of the warmest salmon rivers in Québec, based on more than 10 years of thermal records (Daigle *et al.* 2015). Hydrologically, the Ouelle River is a flashy system and has minimal baseflow contributions, resulting in highly variable summer flow and severe low flow periods (Daigle *et al.* 2015). The Ouelle River flows through two main segments: the mainstem (475 km^2) and La Grande River (375 km^2).

RESULTS

Temporal variation of CTI in the Ouelle and Ste-Marguerite Rivers

Figure 2 shows the computed CTI values for all the stations on the mainstem of the Ouelle River from 2013 to 2021. Only CTIs with excellent or good data quality, based on data availability, were included in this study. As shown in Figure 2, the number of stations varies from year to year due to the data availability and the selection criteria of including only CTI with excellent or good data quality. The years with sufficient data at more than one station (between 3 and 5) are 2014, 2016, 2017, and 2018.

Based on CTI values, the quality of the thermal habitat for salmon was better than for brook trout with a mean CTI value of 79% compared to 48%, respectively. This may be explained by the fact that the salmon are more tolerant of high water temperatures than brook trout. The declining trend lines indicate a degradation in the quality of thermal habitats for both salmon and brook trout, which amplified starting from 2018.

Table 6 | Climate classes based on summer (July–September) (1981–2010) 25th and 75th quartile anomalies of maximum air temperature (ΔT_{airmax}) and total precipitation (ΔP_{tot})

ΔT_{airmax} / ΔP_{toti}	Warm ($\Delta T_{airmaxi}$ > P75%) (P75% = 0.7)	Cool ($\Delta T_{airmaxi}$ > P25%) (P25% = −0.78)	Normal (P25% < $\Delta T_{airmaxi}$ < P75%)
Wet (ΔP_{toti} > P75%) (P75% = 39.15)	Warm-wet	Cool-wet	Normal-wet
Dry (ΔP_{toti} < P25%) (P25% = −38.93)	Warm-dry	Cool-dry	Normal-dry
Normal (P25% < $\Delta P_{tot}i$< P75%)	Warm-normal	Cool-normal	Normal–normal

Note. Index *i* represents the year of interest. The boundary values (25th–75th percentiles (P)) for determining climate classes are written in parentheses.

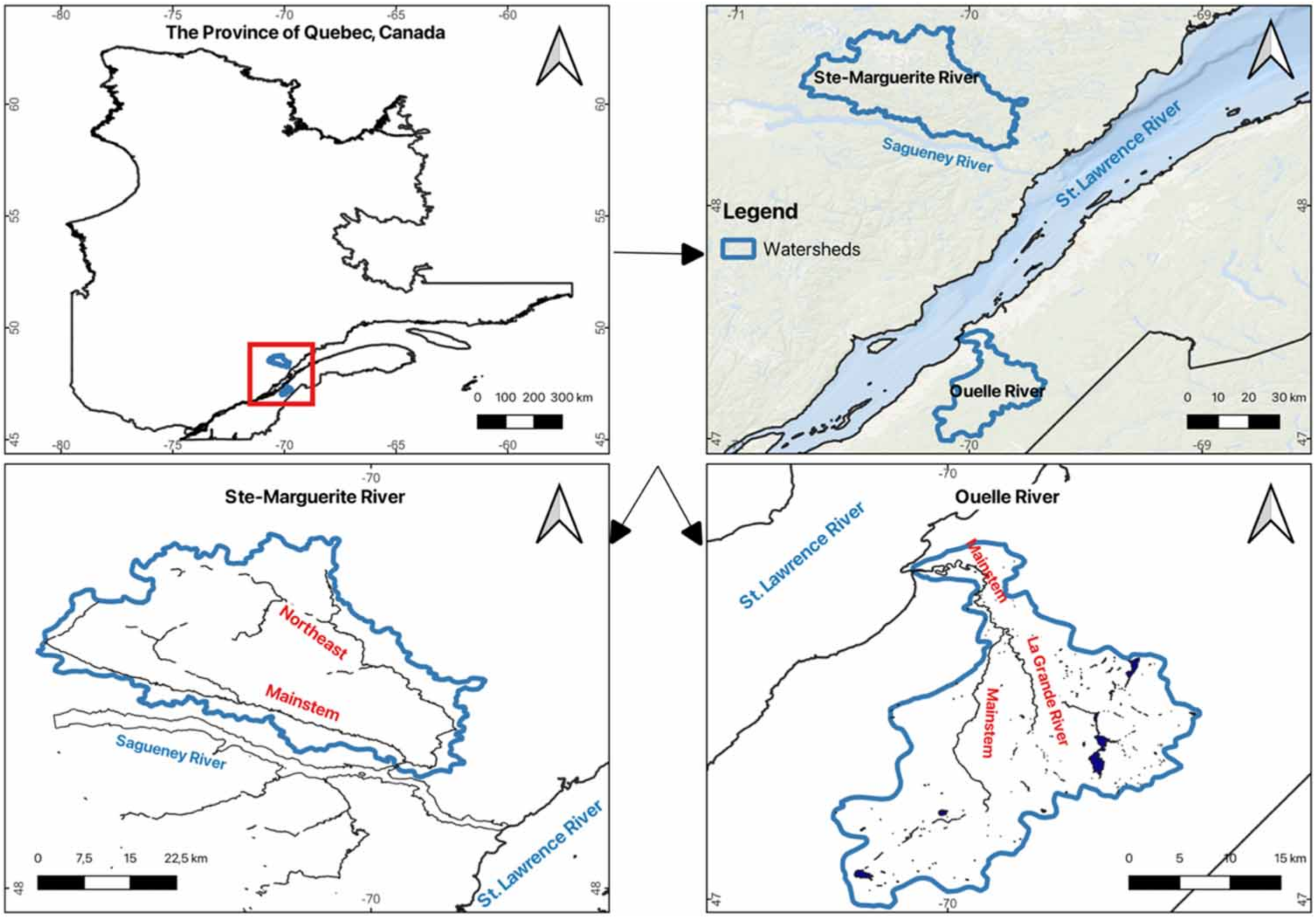

Figure 1 | Locations of the studied rivers: the Ouelle River and Ste-Marguerite River in Québec, Canada.

Figure 3 shows the variation in the mean CTI in the Ouelle River for stations located on the mainstem. Before 2018, the thermal habitat for salmon was overall excellent (CTI $\geq$ 95) except during 2014 when the habitat quality was fair (65 $\leq$ CTI $\leq$ 79). In contrast, starting from 2018, a noticeable degradation in the thermal habitat quality was observed, shifting from excellent to marginal (45 $\leq$ CTI $\leq$ 64). For the brook trout, the thermal quality habitat was worse, varying between average and poor before 2017 (0 $\leq$ CTI $\leq$ 44), with a clear degradation in thermal quality during 2014 and a shift to poor quality condition in 2021. From 2017 to 2021, the climate classes were characterized as warm-dry, which may explain the degradation of thermal quality habitat for both species. In contrast, prior to 2017, the climate classes were overall warm-normal, showing the impact of the precipitations and maximum air temperature on the water temperature and, consequently, on the quality of the thermal habitat.

Figure 4 shows the variation of CTI means for the mainstem's stations of the Ouelle River during 2014, 2016, 2017, and 2018, with a number of stations varying between 3 and 5, as a function of the means of maximum air temperature and total precipitations. It is clear that the lowest CTI values for salmon and brook trout during 2014 (68 and 44%) and 2018 (66 and 47%) were associated with the combined effect of high maximum air temperature (29.4 and 29.5 °C) and relatively low total precipitations (1,018 and 1,171 mm).

In contrast, the relative recovery of thermal quality during 2016 and 2017, particularly for Atlantic salmon, can be explained by a decrease of maximum air temperature (28.9 and 27.6 °C) and relatively high precipitation levels in 2016 (1,251 mm) and consequently higher streamflow. As mentioned before, the climate class in 2016 was warm-normal, while it shifted to warm-dry from 2017.

Figure 5 shows that CTI values were better for both species in the Ste-Marguerite River (a colder system) than in the Ouelle River (a warmer system), with mean values of 99% (salmon) and 75% (brook trout) in the Ste-Marguerite compared to 79%

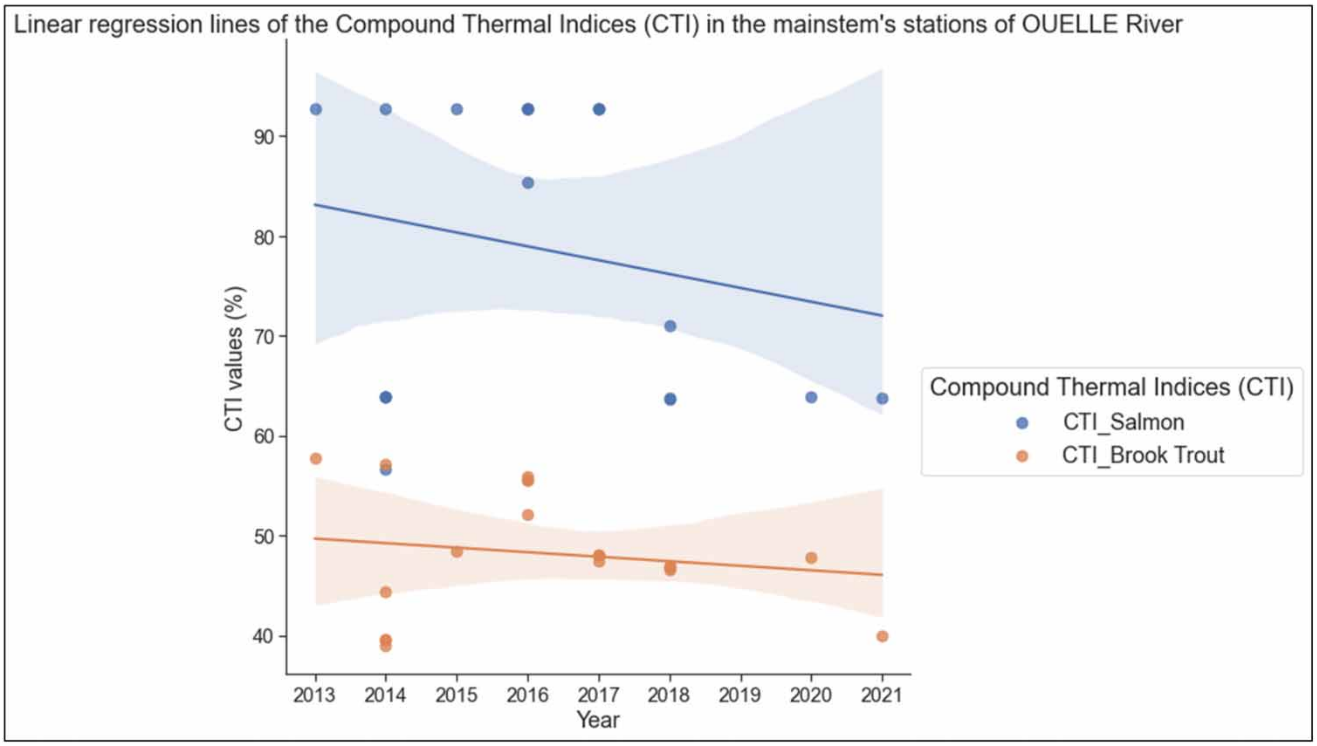

Figure 2 | The CTIs (salmon and brook trout) calculated for each mainstem station for each year (point) in the Ouelle River.

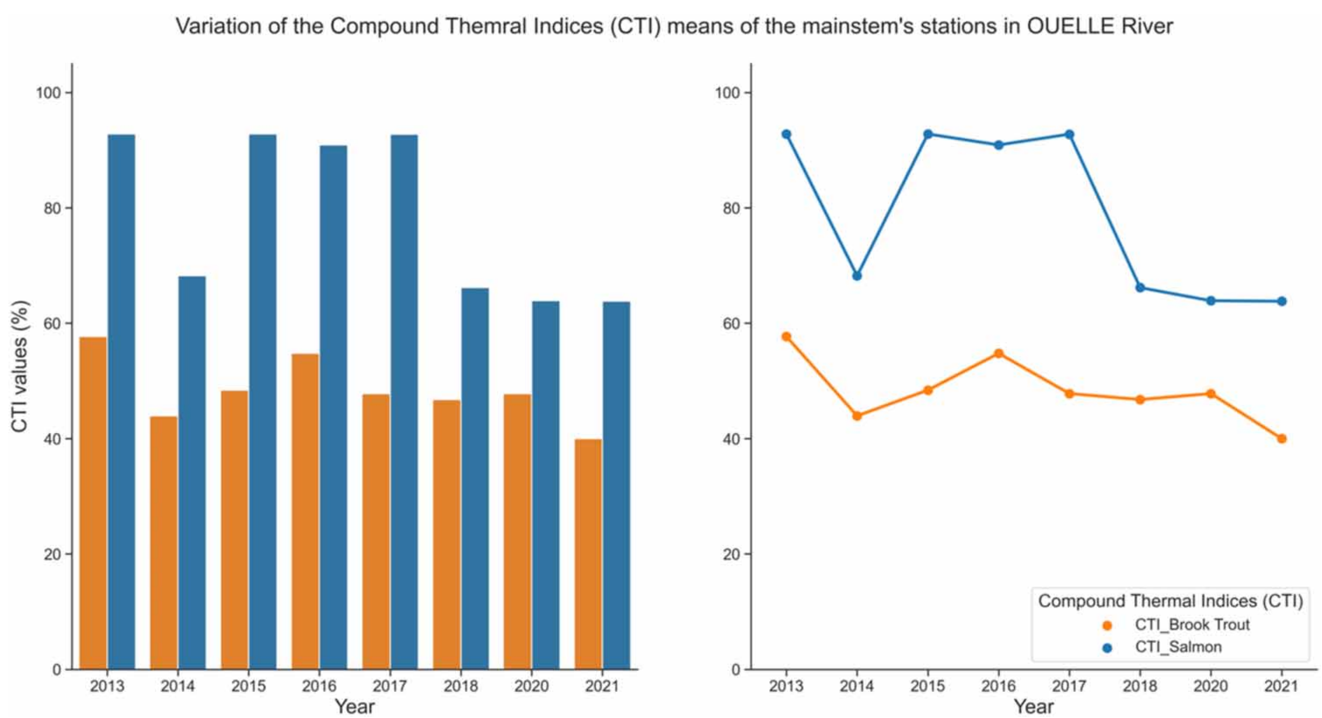

Figure 3 | The variation of CTI means for all mainstem stations at each year in the Ouelle River.

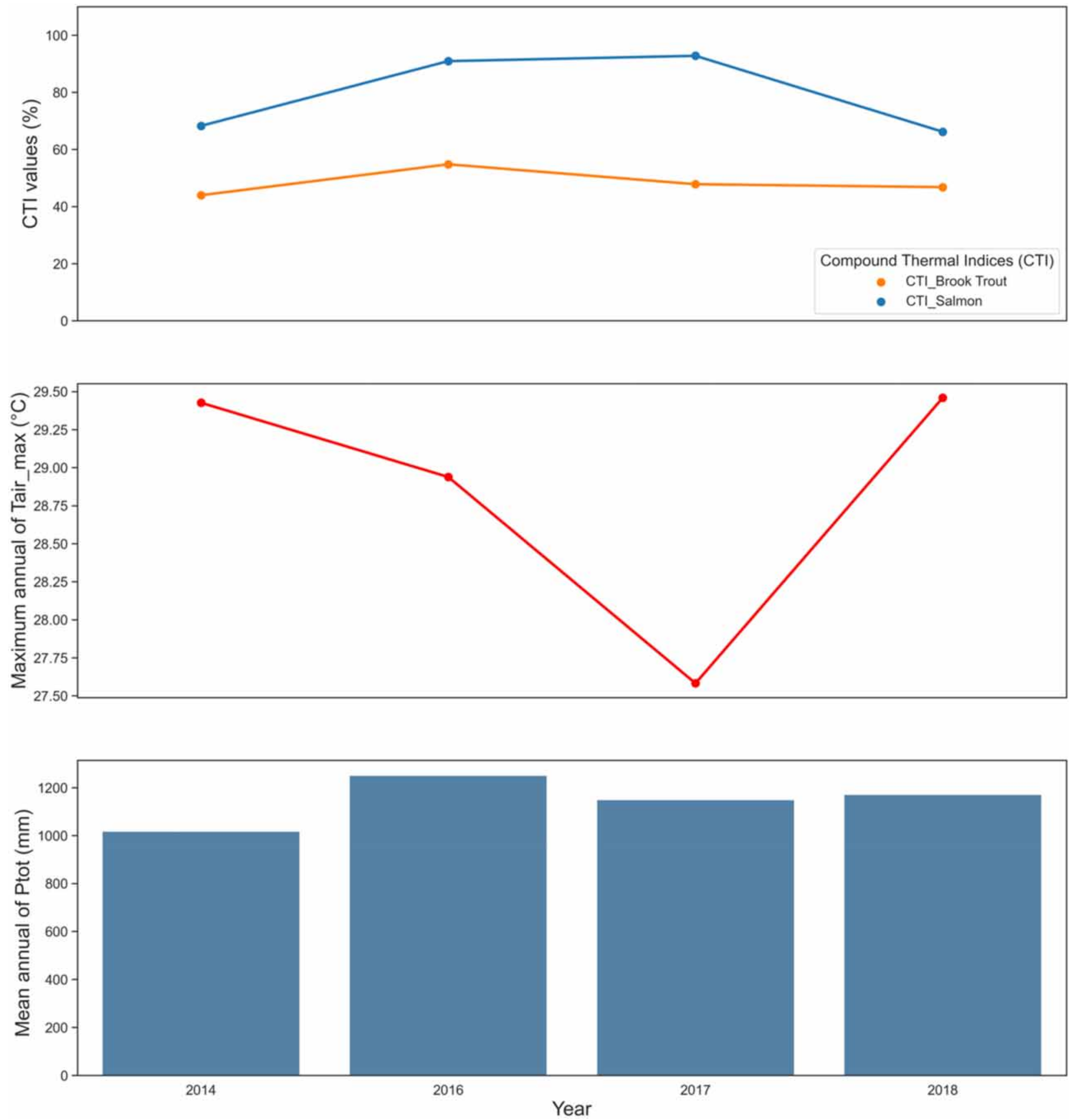

Figure 4 | The variation of CTI means (>= 3 stations) of the mainstem stations of the Ouelle River in relation with their means in maximum air temperature and total precipitations.

(salmon) and 48% (brook trout) in the Ouelle River. However, there is a slight decrease in the habitat thermal quality, with the lowest CTI values falling below 60% for salmon and below 40% for brook trout at some stations during 2022, indicating marginal and poor habitat thermal quality. Similar to previous results, the habitat thermal quality was better for salmon than for brook trout.

Figure 6 displays the variation of CTI mean values in the Ste-Marguerite River for the stations located on the mainstem. The quality of the thermal habitat for salmon was overall excellent from 2013 to 2019 and began to decrease in 2022, but it remained excellent (CTI > 95%). In contrast, for brook trout, the thermal habitat quality was more sensitive, varying from year to year between average and good. In fact, from 2013 to 2016, the quality of the thermal habitat varied between fair ($65 \leq CTI \leq 79$) and good ($80 \leq CTI \leq 94$), corresponding to climate classes that ranged from normal-dry (2013) to warm-normal (2014 to 2016). The lowest CTI value for brook trout (65.6%), indicating fair thermal quality conditions, was observed in 2018, which was associated with warm-dry conditions compared to other years. The recovery of thermal habitat quality began in 2019 (CTI = 74%), associated with normal–normal climate conditions.

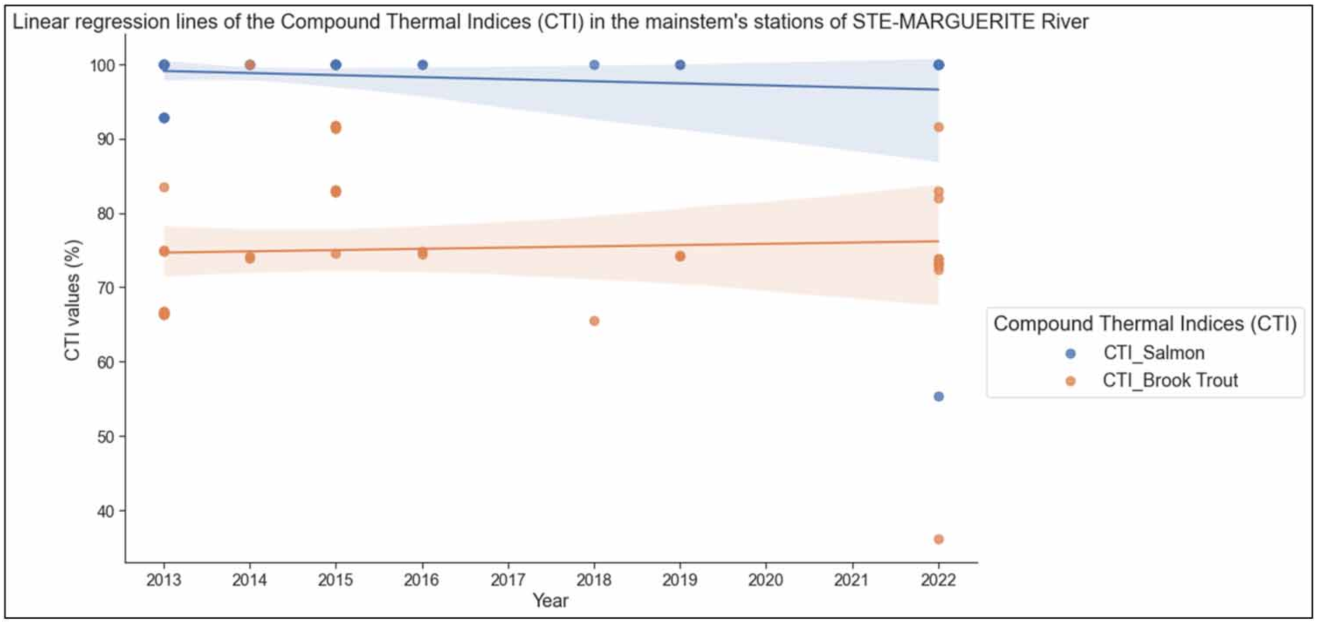

Figure 5 | The CTIs (salmon and brook trout) calculated for each mainstem's station at each year (point) in the Ste-Marguerite River.

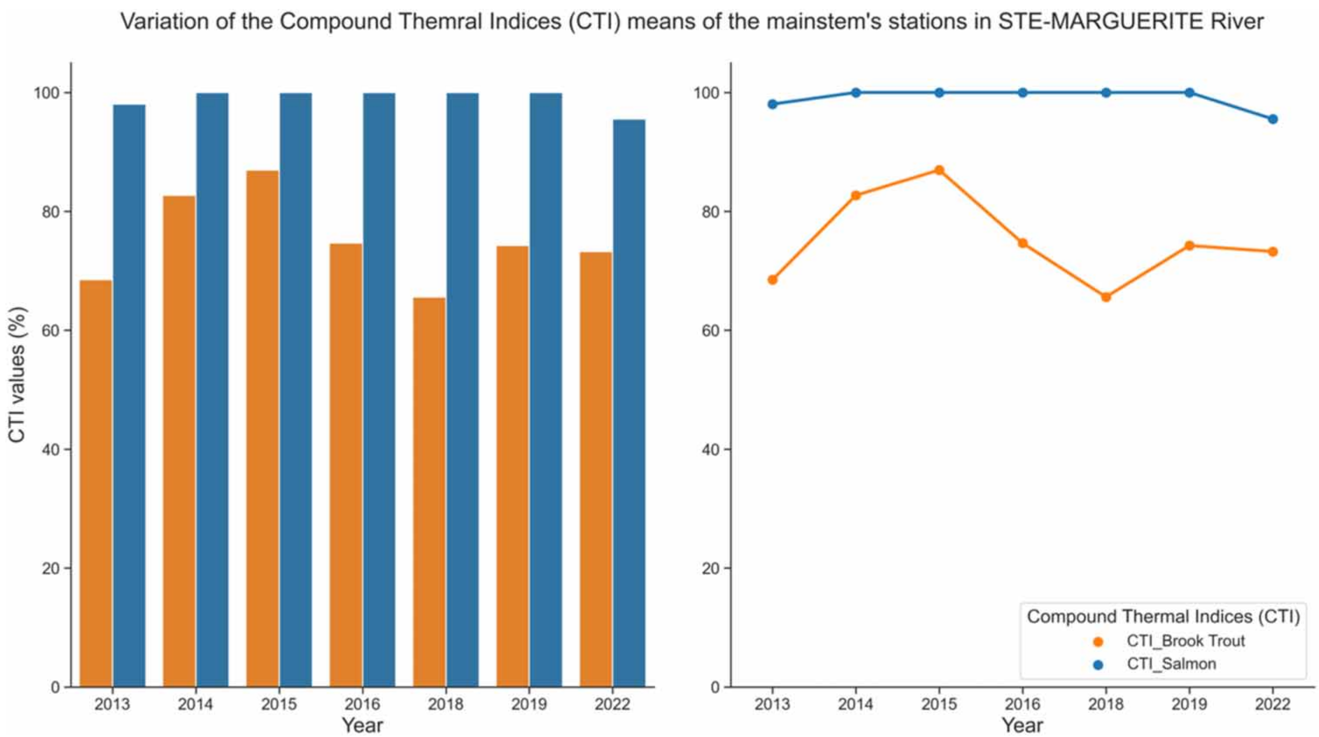

Figure 6 | The variation of CTI means for all mainstem stations at each year in the Ste-Marguerite River.

Figure 7 shows clearly the variation of CTI means in relation to the means of climate conditions (air temperature/precipitations). It is clear that the lowest thermal quality habitat in 2018, i.e., the lowest CTI value (65.6% for brook trout), was associated with the highest air temperature conditions (32.2 °C) and lowest precipitation levels (1,144 mm). The recovery

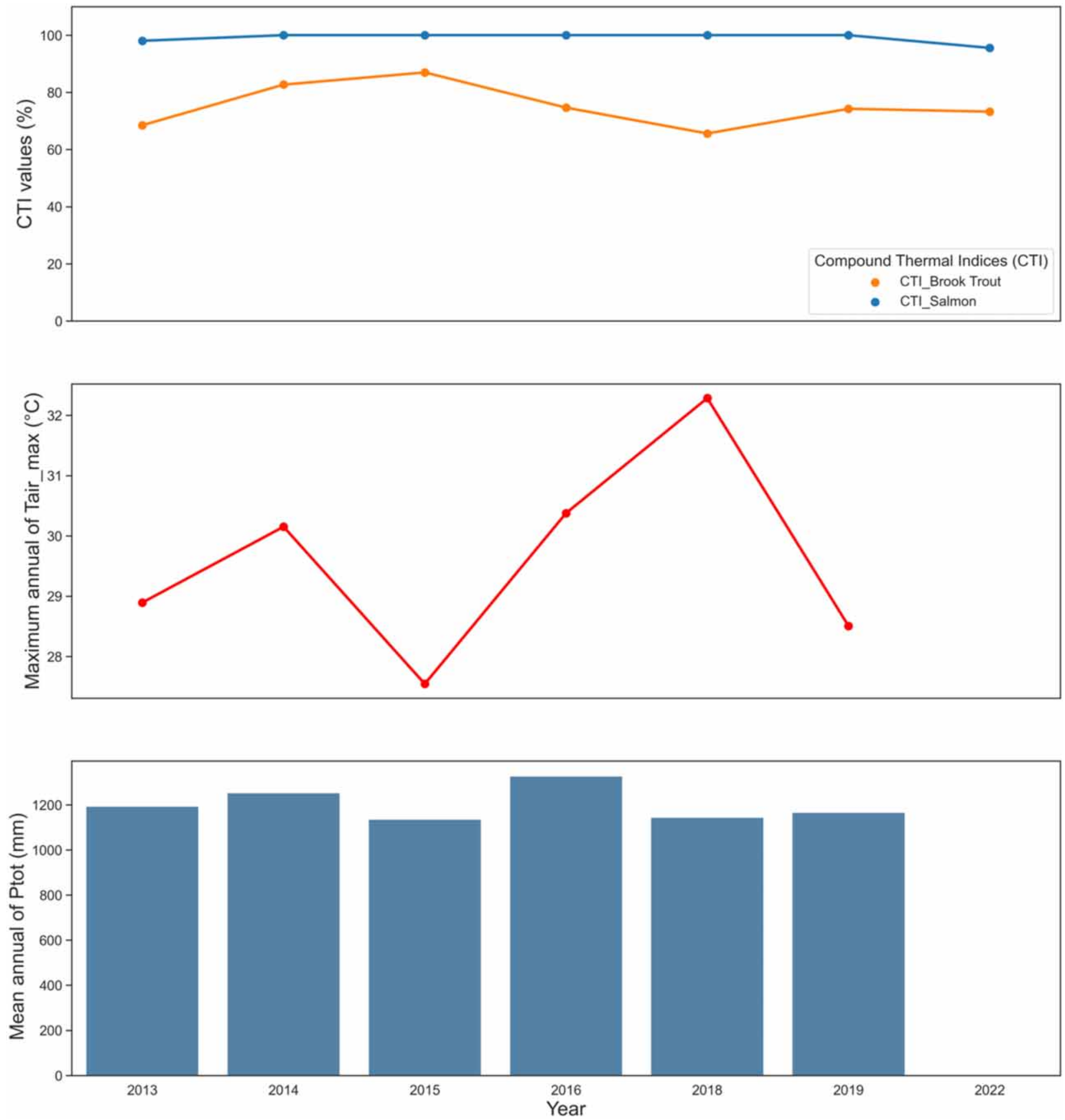

Figure 7 | The variation of CTI means of the mainstem stations of the Ste-Marguerite River in relation with their means in maximum air temperature and total precipitations.

of thermal habitat quality began in 2019 (CTI = 74%), corresponding to normal–normal climate conditions, with a decrease in maximum air temperature (28.5 °C) and an increase in total precipitation (1,166 mm) compared with 2018. In 2015, the best quality of the brook trout thermal habitat (CTI = 87%) was associated with the lowest air temperature conditions (27.5 °C). From 2013 to 2016, good thermal habitat quality conditions for brook trout corresponded to low air temperature and high precipitation levels. The recovery of thermal habitat quality began in 2019 (CTI = 74%), corresponding to normal–normal climate conditions, with a decrease in maximum air temperature (28.5 °C) and an increase in total precipitation (1,166 mm) compared with 2018 (32.2 °C and 1,144 mm).

Spatial variation of CTI in the Ouelle and Ste-Marguerite Rivers

In this section, the spatial variation analysis of the CTI along the rivers included the CTI values computed for all the available stations on the mainstem and tributaries of each river. The stations, with names ending with 'T,' are the stations located on the tributaries, while the rest are located on the mainstem. Figures 8 and 9 show the variation of CTI for salmon and brook trout across all the stations during 2016, which was a warm and normal year. For both species, it is clear that the quality of the thermal habitat was excellent (CTI > 95%) at the tributary stations, while it varied in the rest of the stations between good (for salmon) and marginal (brook trout).

As mentioned before, 2018, a warm and dry year in the Ouelle River, was associated with the lowest thermal quality habitat for both salmon and brook trout (66 and 47%) at the mainstem stations. Figures 10 and 11 display the spatial variation of CTI values in 2018. For salmon, the thermal habitat quality in the tributaries (CTI > 95%) remained excellent, while the habitat quality degraded to marginal and fair at the mainstem stations, with minimum values reaching 63.7% compared with 85.4% in 2016. For brook trout, the excellent quality of the thermal habitat in the tributaries degraded to good quality, while the habitat quality remained marginal in the mainstem, with minimum values reaching 46% compared with 52% in 2016. The degradation in the thermal habitat quality may reflect the severe climate conditions in 2018.

In the Ste-Marguerite River, as previously shown, the quality of the thermal habitat for salmon was overall excellent with slight variation from year to year. However, the quality of the thermal habitat for brook trout was the best in 2015 (87%), indicating good thermal habitat. Figures 12 and 13 show the excellent thermal habitat quality (CTI > 95%) at all mainstem stations and on the Northeast Branch. For brook trout, the thermal quality was overall good on the mainstem and fair at two stations located on the Northeast Branch, implying that this branch was warmer than the Ste-Marguerite mainstem.

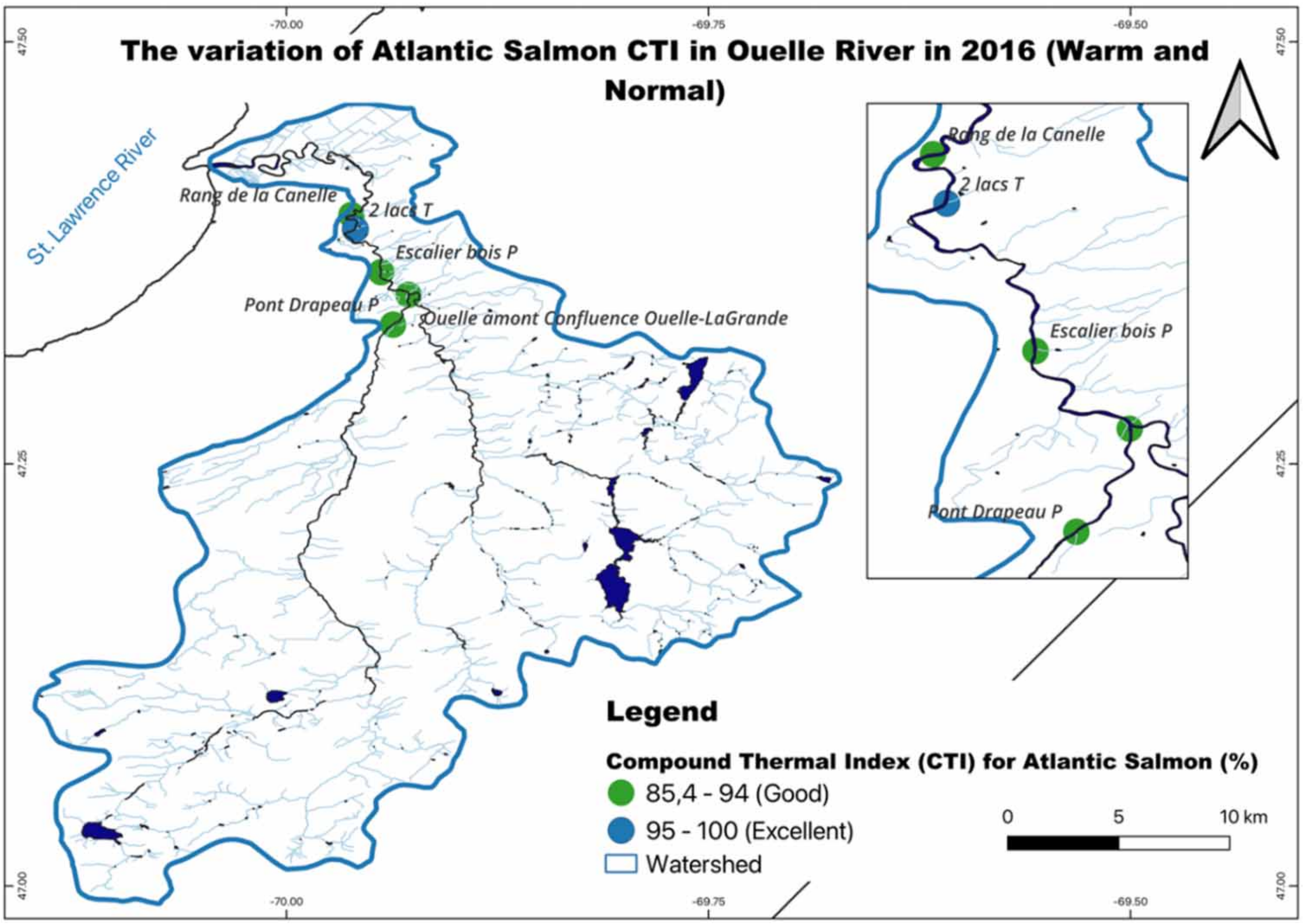

Figure 8 | The spatial variation of salmon CTI in the Ouelle River in 2016 (warm and normal).

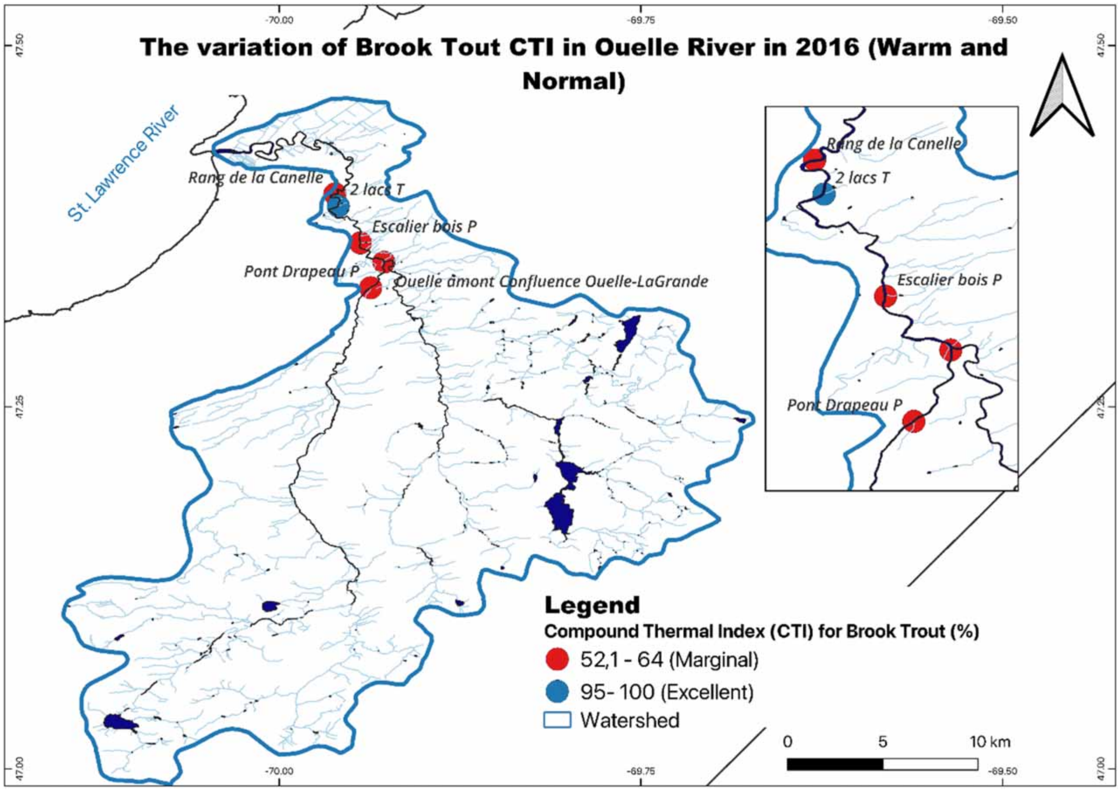

Figure 9 | The spatial variation of brook trout CTI in the Ouelle River in 2016 (warm and normal).

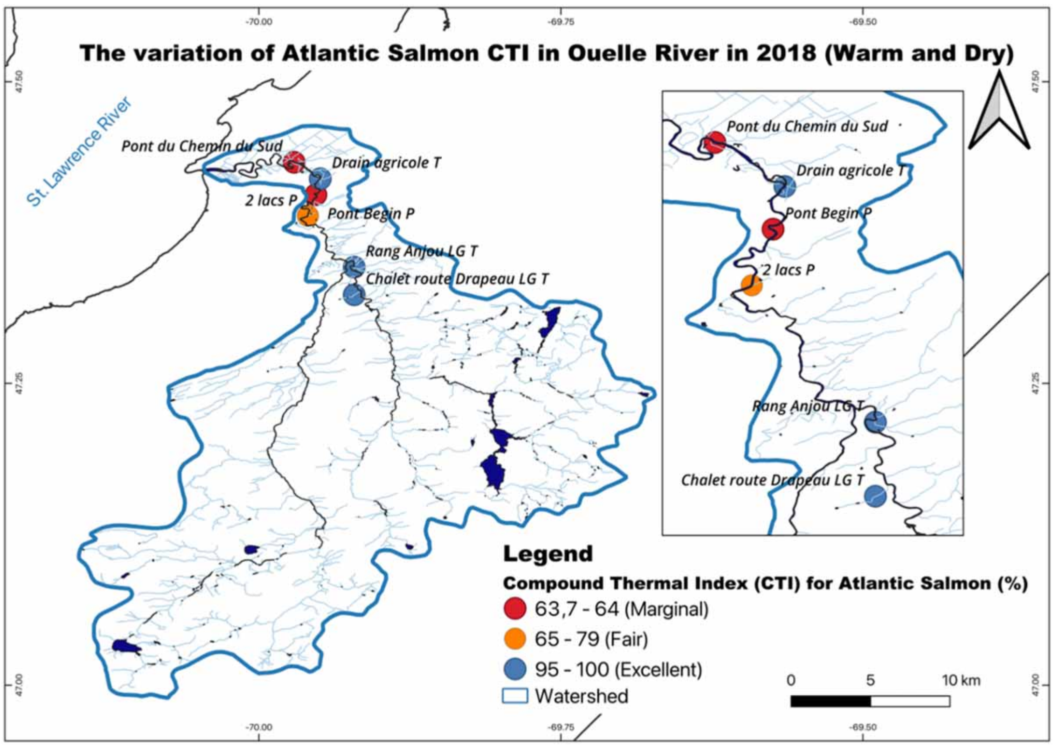

Figure 10 | The spatial variation of salmon CTI in the Ouelle River in 2018 (warm and dry).

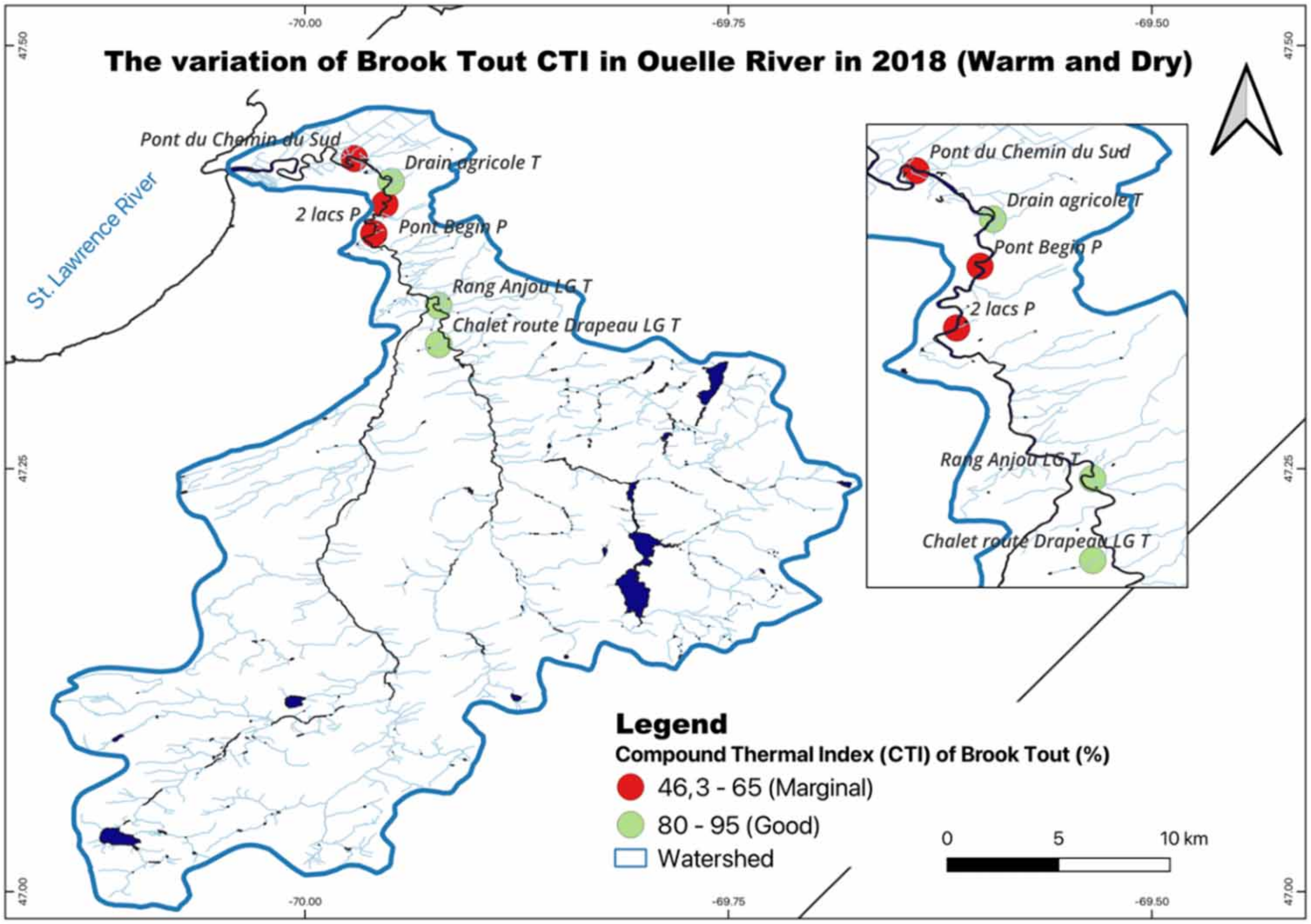

Figure 11 | The spatial variation of brook trout CTI in the Ouelle River in 2018 (warm and dry).

DISCUSSION

In this work, we attempted to adapt the CCME WQI approach to develop a new CTI that includes thermal tolerance for different life stages of two Salmonidae species (Atlantic salmon and brook trout). The goal of this application is to provide a simplified measure (CTI) that synthesizes the quality of the thermal habitat for targeted cold-water species in rivers. This index could easily be used and interpreted by water and fisheries management. To the authors' best knowledge, this study is considered the first application of the CTI for evaluating the habitat's thermal quality of fish.

The CTI was applied to two different salmon rivers in Québec: the Ouelle River (warm) and the Ste-Marguerite River (cool). The analysis of CTI includes examining both temporal and spatial variation along these rivers. Climate contextualization was incorporated into the temporal variation analysis to assess the impact of climate conditions (air temperatures and precipitations) on CTI variation, given that varying ranges of air temperatures and precipitations affect the water temperature and, as a result, the quality of the thermal habitat. The temporal variation analysis of CTI for both rivers, computed for the mainstem's stations, showed that the quality of the thermal habitat for salmon was far better than for brook trout over the study period (e.g., 79–48% in the Ouelle River). This may be explained by the fact that the salmon are more tolerant of high water temperatures than brook trout. Declining trend lines of CTI values over a time period of 9 years (2013–2021) indicate an important degradation in the quality of thermal habitats for both salmon and brook trout in the Ouelle River, particularly in recent years (2018–2021). This is likely the result of the severe climate conditions, given that the climate classes were mainly warm-dry from 2018, associated with high air temperatures and low precipitation levels. The succession of these severe climate conditions may continue to degrade the quality of thermal habitats in the Ouelle River. In the Ste-Marguerite

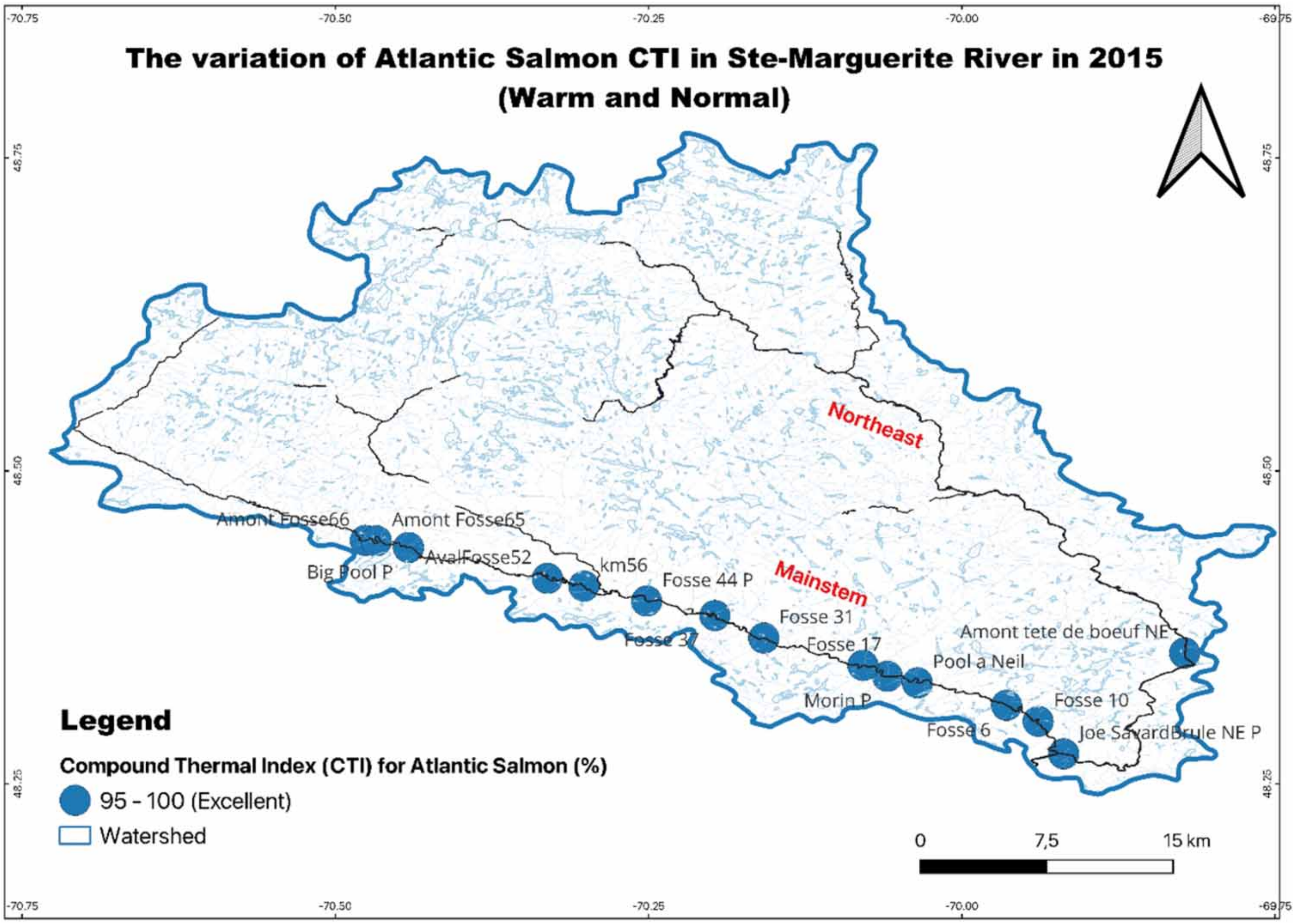

Figure 12 | The spatial variation of salmon CTI in the Ste-Marguerite River in 2015 (warm and normal).

River, a slight degradation was observed in 2022. For both rivers, the quality of the thermal habitat for brook trout was more sensitive and varied from year to year, depending on climate conditions, with the lowest mean values of 47% (marginal thermal conditions) in the Ouelle River and 65% (fair conditions) in the Ste-Marguerite River, observed during the warm-dry year (2018). The recovery of the thermal habitat quality during 2019 in the Ste-Marguerite River for brook trout was associated with normal–normal climate conditions, showing the impact of air temperature and precipitation levels on the water temperature and, as a result, on the thermal habitat. The recovery of the thermal habitat quality in the Ouelle River was associated with a decrease in the maximum air temperature and high precipitation levels.

The spatial variation analysis of the CTI consists of comparing the CTI values computed for all the mainstem and tributary stations of each river. In the Ouelle River, the spatial variability analysis showed that the quality of the thermal habitat for salmon was excellent in the tributary stations (CTI $>$ 95%) during 2016 (warm-normal) and 2018 (warm-dry), while the quality in the mainstem stations varied highly and degraded from fair to marginal. This excellent quality of the thermal habitat in tributary stations, despite the climate conditions during 2018, may be explained by the cooling effect of groundwater contribution. In the case of brook trout, the quality of the thermal habitat in the tributary stations degraded from excellent to good thermal habitat from 2016 to 2018, while it remained marginal at the mainstem stations.

In the Ste-Marguerite River, the thermal habitat quality for salmon was excellent (CTI $>$ 95%) at all mainstem stations and on the Northeast Branch, while it was overall good for brook trout on the mainstem and fair on two stations located on the northeast branch, reflecting that the northeast branch was warmer than the mainstem.

The main study limitation includes the availability of water temperature data. That is why an indicator in CTI data quality was included to assess the quality of the computed CTI.

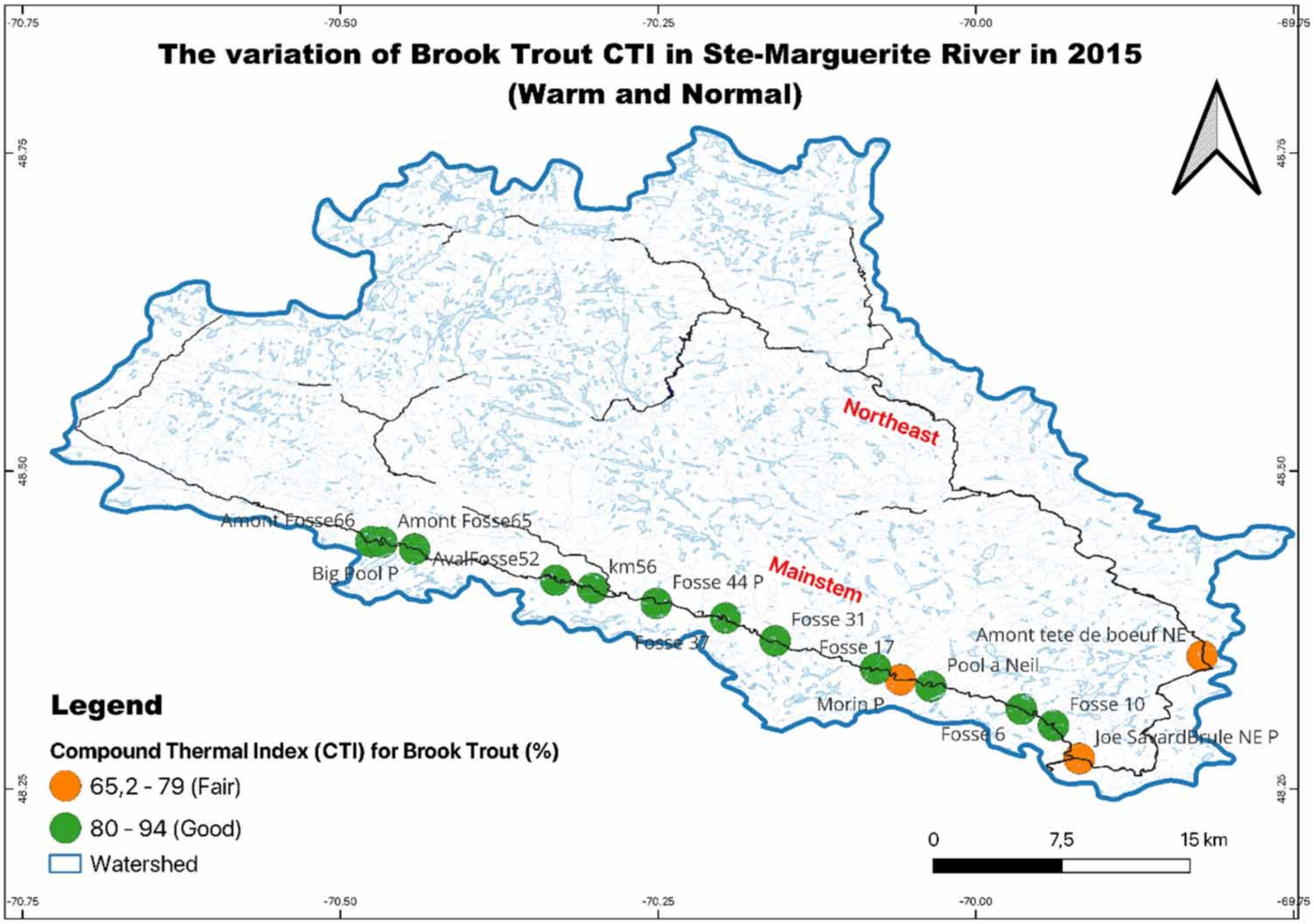

Figure 13 | The spatial variation of brook trout CTI in the Ste-Marguerite River in 2018 (warm and normal).

CONCLUSIONS

This study attempted to develop a CTI, based on the CCME WQI, by combining thermal tolerance for different life stages of targeted species (salmon and brook trout). This compound index can become an easily applicable tool to assess the overall thermal health in rivers and to provide insights into the degradation degree of the thermal habitat due to climate change or human activities. In this study, CTI was applied to two salmon rivers with a natural hydrological regime.

The CTI allowed the detection of the temporal and spatial variability in thermal habitat quality for salmon and brook trout. In fact, the analysis of temporal and spatial variation showed that the degradation of the thermal habitat at mainstem stations was mainly related to climate conditions, particularly during warm-dry years, characterized by high maximum air temperature and low precipitation levels. The recovery of thermal habitat quality was associated with a decrease in maximum air temperature and high precipitation levels, and consequently higher streamflow. This suggests the importance of including the water temperature in determining the environmental flow requirements for rivers (Ferchichi *et al.* 2023) and highlights that the concept of minimum flow during extreme climate conditions may be insufficient to preserve the quality of the thermal habitat for cold-water species. The CTI results showed that the thermal habitat was overall excellent for salmon and good for brook trout in the tributary stations, despite the climate conditions. This suggests that cold groundwater contributions and possibly riparian shading play an important role in mitigating the effect of severe climate conditions and highlights its importance in maintaining thermal refugees. The analysis of CTI indicated that the quality of the thermal habitat is degrading, and this degradation is amplified in recent years, associated with warm-dry conditions. The persistence of these conditions may further deteriorate the thermal quality of habitats for Salmonidae species, particularly in the Ouelle River. Although CTI results showed excellent thermal habitat quality in Ste-Marguerite mainstem (cold river) for salmon and good for brook trout in 2015, the spatial analysis of CTI showed that stations on the northeast branch of the Ste-Marguerite River were warmer than the mainstem's stations with lower habitat thermal quality. Therefore, this detailed assessment of thermal conditions across temporal and spatial scales using CTI may help fisheries managers in developing effective habitat management and conservation planning. Indeed, the CTI allows us to classify the rivers according to the quality of their thermal habitat quality from poor to excellent, showing the importance of this compound index in river classification and monitoring. The CTI could also be applied in regulated river systems to evaluate the quality of fish habitats and assess the impact of human activities on the thermal conditions.

In order to protect the quality of thermal habitats, modeling CTI scenarios for the targeted fishes, by projecting future water temperature under different climate scenarios, allows us to assess the degree of degradation of thermal habitat quality due to climate change. These projections may help us to develop more adaptive management strategies to preserve the cold-water refugees and minimize the effect of severe climate conditions.

The findings of this study highlight the importance of CTI as an easy indicator of thermal habitat quality, which could be easily computed and interpreted by the fisheries managers, helping in establishing effective habitat management strategies for the conservation of aquatic habitats.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abidi, O., St-Hilaire, A., Ouarda, T. B. M. J., Charron, C., Boyer, C. & Daigle, A. (2022) Regional thermal analysis approach: a management tool for predicting water temperature metrics relevant for thermal fish habitat, *Ecological Informatics*, **70** (September), 101692. https://doi.org/10.1016/j.ecoinf.2022.101692.

Beaufort, A., Diamond, J. S., Sauquet, E. & Moatar, F. (2021) The Thermal Peak: A Simple Stream Temperature Metric at Regional Scale, Hydrology & Earth System Sciences (preprint). https://doi.org/10.5194/hess-2021-218.

Betis, H., St-Hilaire, A., Fortin, C. & Duchesne, S. (2020) Development of a water quality index for watercourses downstream of harvested peatlands, *Water Quality Research Journal*, **55** (2), 119–131. https://doi.org/10.2166/wqrj.2020.007.

Boyer, C., St-Hilaire, A. & Bergeron, N. E. (2021) Defining river thermal sensitivity as a function of climate, *River Research and Applications*, **37** (10), 1548–1561. https://doi.org/10.1002/rra.3862.

Breau, C. (2013) Knowledge of fish physiology used to set water temperature thresholds for in-season closures of Atlantic salmon (*Salmo salar*) recreational fisheries, DFO Can. Sci. Advis. Sec. Res. Doc., 2012/163, iii +24.

Brett, J. R. (1944) Some lethal temperature: relations of Algonquin park fishes. University of Toronto Studies, Biological Series, No. 52, *Publications of the Ontario Fisheries Research Laboratory*, **63**, 1–49.

Bujold, J.-N. & Vachon, M. (2016) Guide d'identification de frayères à omble de fontaine dans les cours d'eau, Ministère des Forêts, de la Faune et des Parcs. Quebec: Dépôt légal - Bibliothèque nationale du Québec, 1e trimestre, 2016. ISBN : 978-2-550-74828-1.

Canadian Council of Ministers of the Environment (2001) Canadian water quality guidelines for the protection of aquatic life: CCME Water Quality Index 1.0, User's Manual. In: *Canadian environmental quality guidelines, 1999,* Winnipeg: Canadian Council of Ministers of the Environment.

Canadian Council of Ministers of the Environment (2017) Canadian water quality guidelines for the protection of aquatic life: CCME Water Quality Index, User's Manual – 2017 Update. In: Canadian environmental quality guidelines, 1999, Winnipeg: Canadian Council of Ministers of the Environment.

Chadwick, J. G. & McCormick, S. D. (2017) Upper thermal limits of growth in brook trout and their relationship to stress physiology, *Journal of Experimental Biology*, **220** (21), 3976–3987. https://doi.org/10.1242/jeb.161224.

Chang, H. & Psaris, M. (2013) Local landscape predictors of maximum stream temperature and thermal sensitivity in the Columbia River basin, USA, *Science of The Total Environment*, **461–462** (September), 587–600. https://doi.org/10.1016/j.scitotenv.2013.05.033.

Daigle, A., Jeong, D. I. & Lapointe, M. F. (2015) Climate change and resilience of tributary thermal refugia for salmonids in Eastern Canadian rivers, *Hydrological Sciences Journal*, **60** (6), 1044–1063. https://doi.org/10.1080/02626667.2014.898121.

Daigle, A., Boyer, C. & St-Hilaire, A. (2019) A standardized characterization of river thermal regimes in Québec (Canada), *Journal of Hydrology*, **577** (October), 123963. https://doi.org/10.1016/j.jhydrol.2019.123963.

DFO (2012) Temperature threshold to define management strategies for Atlantic salmon (*Salmo Salar*) *Fisheries under Environmentally Stressful Conditions*. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2012/019.

Elliott, J. M. (1981) Some aspects of thermal stress on freshwater teleosts. In A.D. Pickering (Ed.): *Stress and Fish*, London: Academic Press, pp. 209–245

Elliott, J. M. (1991) Tolerance and resistance to thermal stress in juvenile Atlantic salmon, *Salmo salar*, *Freshwater Biology*, **25** (1), 61–70. https://doi.org/10.1111/j.1365-2427.1991.tb00473.x.

Elliott, J. M. & Elliott, J. A. (2010) Temperature requirements of Atlantic salmon *Salmo salar*, brown trout *Salmo trutta* and Arctic charr *Salvelinus alpinus*: predicting the effects of climate change, *Journal of Fish Biology*, **77** (8), 1793–1817. https://doi.org/10.1111/j.1095-8649.2010.02762.x.

Ferchichi, H., St-Hilaire, A., Berthot, L. & Caissie, D. (2023) Augmenting environmental flow information with water temperature: case study in Eastern Canada, *Canadian Water Resources Journal/Revue Canadienne Des Ressources Hydriques*, **48** (2), 111–131. https://doi.org/10.1080/07011784.2022.2157334.

Graham, J. M. (1949) Some effects of temperature and oxygen pressure on the metabolism and activity of the speckled trout, *Salvelinus fontinalis*, *Canadian Journal of Research*, **27d** (5), 270–288. https://doi.org/10.1139/cjr49d-024.

Grande, M. & Andersen, S. (1991) Critical thermal maxima for young salmonids, *Journal of Freshwater Ecology*, **6** (3), 275–279. https://doi.org/10.1080/02705060.1991.9665304.

Hokanson, K. E. F., Howard McCormick, J., Jones, B. R. & Tucker, J. H. (1973) Thermal requirements for maturation, spawning, and embryo survival of the brook trout, *Salvelinus fontinalis*, *Journal of the Fisheries Research Board of Canada*, **30** (7), 975–984. https://doi.org/10.1139/f73-158.

Jonsson, B. & Jonsson, N. (2009) A review of the likely effects of climate change on anadromous Atlantic salmon *Salmo salar* and brown trout *Salmo trutta*, with particular reference to water temperature and flow, *Journal of Fish Biology*, **75** (10), 2381–2447. https://doi.org/10.1111/j.1095-8649.2009.02380.x.

Karr, J., Fausch, K., Angermeier, P. L., Yant, P. R. & Schlosser, I. J. (1986) *Assessing Biological Integrity in Running Waters: A Method and Its Rationale*. Illinois: Illinois Natural History Survey. Special Publication 5 (September).

Kilgour, D. M., McCauley, R. W. & Kwain, W. (1985) Modeling the lethal effects of high temperature on fish, *Canadian Journal of Fisheries and Aquatic Sciences*, **42** (5), 947–951.

Leach, J. A. & Dan Moore, R. (2019) Empirical stream thermal sensitivities may underestimate stream temperature response to climate warming, *Water Resources Research*, **55** (7), 5453–5467. https://doi.org/10.1029/2018WR024236.

Maheu, A., Poff, N. L. & St-Hilaire, A. (2016) A classification of stream water temperature regimes in the conterminous USA, *River Research and Applications*, **32** (5), 896–906. https://doi.org/10.1002/rra.2906.

Ouellet, V. & Daniels, M. (2021) Brook trout (Salvelinus fontinalis) and brown trout (Salmo trutta) summer thermal habitat use in streams with sympatric populations, *Journal of Thermal Biology*, **98**, 102931. https://doi.org/10.1016/j.jtherbio.2021.102931.

Oyinlola, M. A., Khorsandi, M., Penman, R., Earhart, M. L., Arsenault, R., Brauner, C. J. & St-Hilaire, A. (2023) Hydrothermal impacts of water release on early life stages of white sturgeon in the Nechako River, B.C. Canada, *Journal of Thermal Biology*, **117** (October), 103682. https://doi.org/10.1016/j.jtherbio.2023.103682.

Robinson, J. M., Josephson, D. C., Weidel, B. C. & Kraft, C. E. (2010) Influence of variable interannual summer water temperatures on brook trout growth, consumption, reproduction, and mortality in an unstratified Adirondack lake, *Transactions of the American Fisheries Society*, **139** (3), 685–699. https://doi.org/10.1577/T08-185.1.

Smalås, A., Primicerio, R., Kahilainen, K. K., Terentyev, P. M., Kashulin, N. A., Zubova, E. M. & Amundsen, P. A. (2023) Increased importance of cool-water fish at high latitudes emerges from individual-level responses to warming, *Ecology and Evolution*, **13** (6), e10185. https://doi.org/10.1002/ece3.10185.

Van Leeuwen, T. E., Lehnert, S. J., Breau, C., Fitzsimmons, M., Kelly, N. I., Dempson, J. B., Neville, V. M., Young, M., Keefe, D., Bird, T. J. & Cote, D. (2023) Considerations for water temperature-related fishery closures in recreational Atlantic salmon (*Salmo salar*) catch and release fisheries: a case study from Eastern Canada, *Reviews in Fisheries Science & Aquaculture*, **31** (4), 598–619. https://doi.org/10.1080/23308249.2023.2242959.

Wilbur, N. M., O'Sullivan, A. M., MacQuarrie, K. T. B., Linnansaari, T. & Allen Curry, R. (2020) Characterizing physical habitat preferences and thermal refuge occupancy of brook trout (*Salvelinus fontinalis*) and Atlantic Salmon (*Salmo salar*) at high river temperatures, *River Research and Applications*, **36** (5), 769–783. https://doi.org/10.1002/rra.3570.

Wilkie, M. P., Brobbel, M. A., Davidson, K. G., Forsyth, L. & Tufts, B. L. (1997) Influences of temperature upon the postexercise physiology of Atlantic salmon (*Salmo salar*), *Canadian Journal of Fisheries and Aquatic Sciences*, **54** (3), 503–511. https://doi.org/10.1139/f96-305.

First received 30 July 2024; accepted in revised form 23 December 2024. Available online 22 January 2025