Arctic Science

OPEN ACCESS | Research Article

Assessing the potential for Atlantic salmon (*Salmo salar*) colonization of Nunavik's Arctic and subarctic rivers by 2070–2100

P. Poulin[a], **A. St-Hilaire**[a,b], **C. Boyer**[a], **and N. E. Bergeron**[a]

[a]Institut National de la Recherche Scientifique, Centre Eau Terre Environnement, QB, Canada; [b]Canadian River Institute, University of New Brunswick, Fredericton, Canada

Corresponding author: **André St-Hilaire** (email: andre.st-hilaire@inrs.ca)

Abstract

In Nunavik, Québec, Canada, Atlantic salmon (*Salmo salar*) populations reach their northern limit in four rivers of southern Ungava Bay. With projected river warming from climate change, this study assesses the potential for Atlantic salmon to colonize new rivers in Nunavik by modelling water temperatures and evaluating river accessibility. Migration barriers were identified with a literature review, topographic data, and satellite imagery. Water temperatures were modelled with a generalized additive model using ERA5-Land air temperature, observed daily mean temperatures, and water surface temperature estimated from Landsat imagery. Our projections indicate an average increase of the rivers mean summer temperatures of 1.2–2.7 °C by the end of the century, enhancing thermal conditions in current salmon rivers with more days with optimal growth temperatures (16–20 °C) while still having limited days with thermal stress (>22 °C). By 2100, other Ungava Bay rivers may be colonized, as most are accessible and expected to reach more suitable temperatures. However, Nunavik's northernmost rivers would remain too cold and colonization of the Hudson Bay watershed appears less likely due to the inaccessibility of most rivers and their distance from established anadromous populations.

Key words: Atlantic salmon, Nunavik, climate change, river temperature modelling, generalized additive model, Landsat thermal remote sensing

Résumé

Au Nunavik, Québec, Canada, les populations de saumon atlantique (*Salmo salar*) sont à leur limite nordique dans quatre grandes rivières du sud de la baie d'Ungava. Avec le réchauffement prévu des rivières en raison des changements climatiques, cette étude évalue le potentiel de colonisation de nouvelles rivières au Nunavik par le saumon atlantique en modélisant les températures de l'eau et en évaluant l'accessibilité des rivières. Les obstacles à la migration ont été identifiés à l'aide d'une revue de la littérature, de données topographiques et d'images satellites. Les températures de l'eau ont été modélisées avec un modèle additif généralisé utilisant les données de température de l'air d'ERA5-Land, des températures moyennes journalières observées et les températures de surface de l'eau estimées à partir des images thermiques Landsat. D'ici la fin du siècle, nos projections indiquent une augmentation moyenne des températures estivales moyennes des rivières de 1,2 à 2,7 °C améliorant les conditions thermiques des rivières à saumon actuelles avec plus de jours à des températures optimales de croissance (16–20 °C) tout en ayant peu de jours avec un stress thermique (>22 °C). D'ici 2100, d'autres rivières de la baie d'Ungava pourraient être colonisées, car la plupart sont accessibles et devraient avoir des conditions thermiques plus adéquates. Cependant, les rivières plus au nord du Nunavik resteraient trop froides et la colonisation du bassin versant de la baie d'Hudson semble moins probable en raison de l'inaccessibilité de la plupart des rivières et de leur distance par rapport aux populations anadromes existantes. [*Ceci est une traduction fournie par l'auteur du résumé en anglais.*]

Mots-clés : saumon atlantique, Nunavik, changements climatiques, modélisation des températures en rivières, modèle additif généralisé, télédétection thermique Landsat

1. Introduction

Atlantic salmon (*Salmo salar*) is an anadromous species found in the North Atlantic and Arctic Oceans, migrating and reproducing in rivers across North America and Europe. Optimal growth occurs at water temperatures between 16 and 20 °C (Elliott and Elliott 2010), while thermal stress beginning when daily temperatures exceed 22 °C (Finstad et al. 2004; Elliott and Elliott 2010). It has a broad latitudinal distribution, ranging from temperate to subarctic climates, from its southern limits in New England (USA) and Portugal to its northern limits roughly following the treeline (Maoiléidigh et al. 2018). Freshwater conditions across its range are highly variable, requiring Atlantic salmon to exhibit considerable adaptability to local environments. The northernmost populations are found in Europe in the rivers of northern Norway at about 70° North (Bilous and Dunmall 2020) at the treeline. In North America, the northernmost population is in the Kapisillit River (64°N), the sole Arctic population of Atlantic salmon in Greenland, which is facing a decline due to overfishing (Hedeholm et al. 2018). At 58° north, populations are established in the four major watersheds that drain into the southern Ungava Bay: Leaf River, Koksoak River, Whale River, and George River. These watersheds are located in Nunavik, the northern tip of the province of Quebec (Canada) in a subarctic climate. Nearby, on the Labrador Coast, Atlantic salmon is found in rivers up to 57° north, with a population in Webb Creek, but none were reported farther north (Anderson 1985; Andrews and Coffey 2009). For the marine distribution in northern Canada, the Atlantic salmon is common in the Labrador Sea and the Ungava Bay, but also present more sporadically in the Hudson Strait and Baffin Bay (Andrews and Coffey 2009; Bilous and Dunmall 2020).

The rivers in Nunavik are cold and the Atlantic salmon is therefore characterized by a slow growth, resulting in older (3–7 years) and bigger smolts compared to meridional populations (Power 1958; Lee and Power 1976). The Atlantic salmon in Nunavik also adopts alternative migratory patterns: not all individuals, of both sexes, within a same genetic population (Carbonneau et al. 2024), migrate to the sea. It is an example of the partial migration concept (Chapman et al. 2012) where anadromous salmon cohabit with resident salmon that stay their entire life in freshwater even without migratory obstacles. In Nunavik, there are also estuarine salmon that migrate only to the estuary of their river for feeding without going to the sea and some individuals adopt a mix of these migratory patterns (Robitaille et al. 1984; Belzile et al. 1990; Brûlé 2022). It was suggested that the estuarine migration pattern was caused by the Ungava Bay remaining too cold for too long in the spring, which prevents salmon from going to sea until late in the season resulting in a proportion of individuals remaining in the estuary instead of migrating at sea (Lee and Power 1976; Power 1981). Cold sea temperature, along with the estuarine behaviour, could limit the potential of Atlantic salmon to colonize new rivers in the region. These unique estuarine and mix migratory behaviours are likely a consequence of the hardness of the conditions of the environment (Power 1981; Robitaille et al. 1986; Brûlé 2022). They were particularly studied in the Koksoak watershed but are also observed in the three other Atlantic salmon rivers of Nunavik (Brûlé 2022; Carbonneau et al. 2024). It shows the high adaptation of the species to its local environment. Local adaptation is particularly present in wild population and is associated with low dispersal rates and strong homing behaviour (Keefer and Caudill 2014; Lamarins et al. 2024). However, under harsher environmental conditions, such as increased water temperature or competition, straying behaviour may be induced (Nielsen et al. 2013; Birnie-Gauvin et al. 2019). Nunavik is also known for the Atlantic salmon present in the estuary of the Nastapoka River (57°N) on the Hudson Bay Coast. These individuals have adapted to live in a small brackish estuary located below an impassable waterfall and are likely originating from upstream landlocked populations (April et al. 2023). The current status of the Ungava Bay Atlantic salmon populations is unknown due to general lack of information on the population stocks (COSEWIC 2011)

Atlantic salmon is currently absent from rivers further north in Nunavik due to water temperatures being too cold for population establishment (Salonius 1973; Power et al. 2008). However, with climate change, river temperatures are expected to rise (Jonsson and Jonsson 2009; Hedger et al. 2013; Van Vliet et al. 2013; Santiago et al. 2020; Botero-Acosta et al. 2022) and salmonid distributions are projected to shift northward (Jonsson and Jonsson 2009; Dunmall et al. 2016). As a result, Atlantic salmon could expand into more rivers across the Arctic and subarctic, including those in Nunavik. At the same time, warming may also increase the occurrences of thermal stress: in Labrador, some subarctic populations have already experienced incipient lethal water temperatures for 14 consecutive days (Geissinger et al. 2024).

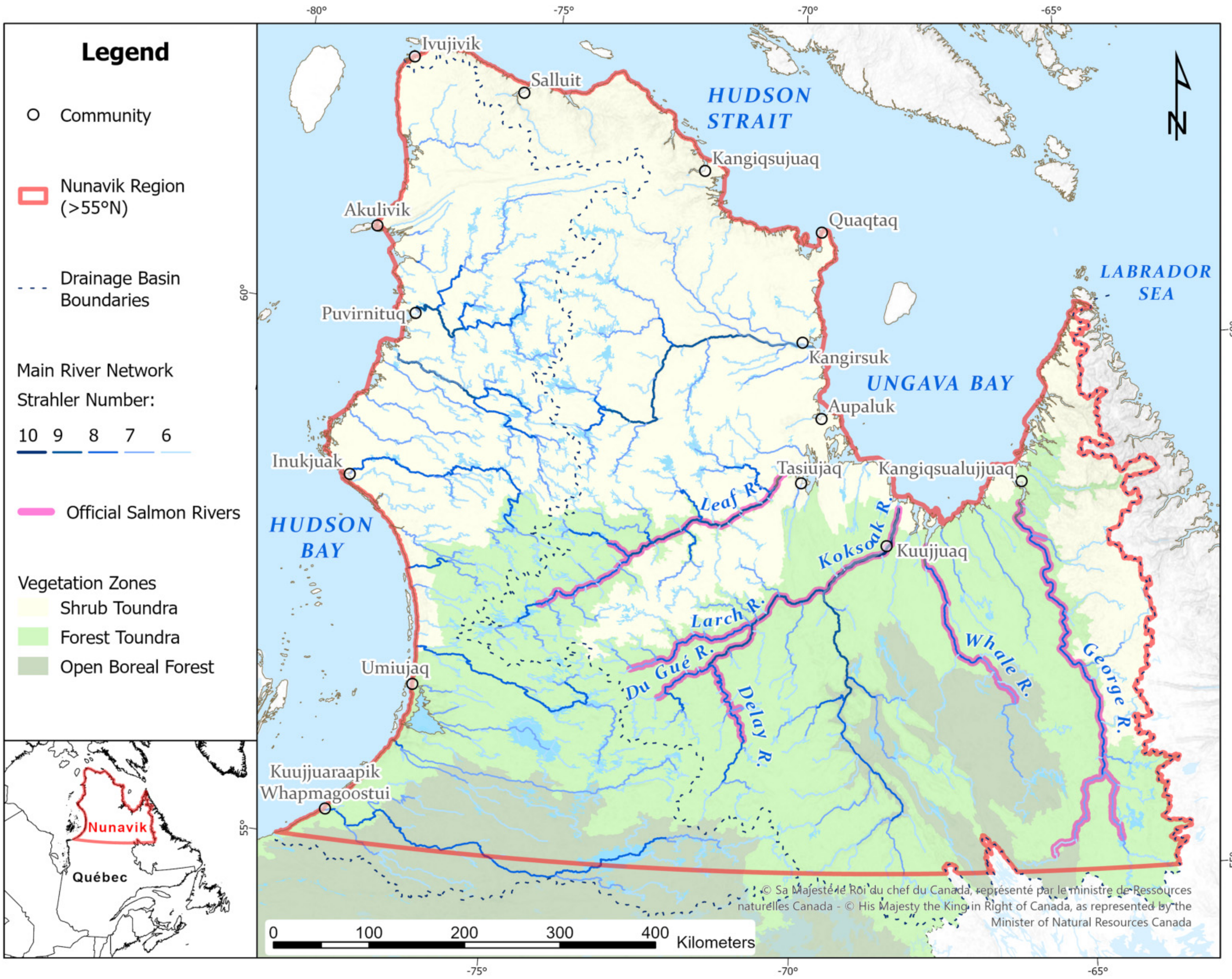
To study water temperatures in areas with limited water temperature observations, such as Nunavik, the use of thermal remote sensing data becomes a great alternative to in situ measurements (Handcock et al. 2006; Dugdale 2016; Rincón et al. 2023; St-Hilaire et al. 2023). In recent years, many studies have used the freely available thermal infrared data from Landsat satellite missions to estimate the surface temperature of waterbodies (Martí-Cardona et al. 2019; Tavares et al. 2020; Vanhellemont 2020; Daigle et al. 2022; Dyba et al. 2022; Halverson et al. 2022; Rincón et al. 2023). Indeed, it can provide spot estimations of the water surface temperature (WST) for the last 40 years. However, it is limited to large rivers that have a minimal width of 180–360 m, depending on the Landsat mission, due to the mixing of water and non-water pixels (Handcock et al. 2006). Estimating WST on smaller streams is possible but require a computationally intensive unmixing algorithm (Martí-Cardona et al. 2019).

To model the water temperature, statistical models have been tested and found to be efficient in simulating the river temperature from air temperature (Caissie et al. 2001). Among the statistical models, the generalized additive model (GAM), a nonlinearnon-parametric regression model, has proven to perform better than other models to predict water temperature (Laanaya et al. 2017; Abidi et al. 2022; Ouarda et al. 2022).

The aim of the study is to determine if new rivers in Nunavik could be colonized by Atlantic salmon by the end of the century in terms of accessibility and suitable summer water temperature. These are only two factors that will affect the potential colonization of new rivers by the Atlantic salmon. Many more aspects will impact the colonization success such as the availability of suitable habitat and the interactions with fish species already present (Nielsen et al. 2013; Bilous and Dunmall 2020), but the focus of this study is only on the river accessibility and the river temperature.

A literature review was first conducted to compile all known records of Atlantic salmon outside the official salmon

Fig. 1. Map of the study site with the Nunavik territory boundary (MRNF 2018), the main hydrographic network (MRNF 2019) and the vegetation zone (Morneau et al. 2021). "Official Salmon Rivers" is a designation granted by the Québec provincial government for conservation purposes, applied to the principal rivers within watersheds where Atlantic salmon populations are currently established. Coordinate system: NAD 1983 CSRS; Projection: Quebec Lambert Conformal Conic.



rivers of Nunavik, to verify whether the species is already present elsewhere and update its regional distribution. For instance, in Nunavut, Bilous and Dunmall (2020) collated many occurrences of Atlantic salmon far north in coastal areas and surprisingly, in freshwater also. Next, river accessibility across Nunavik was assessed to determine which rivers and reaches have no physical barriers and verify whether Atlantic salmon absence in some rivers may be due to impassable obstacles. Such obstacles were identified using literature, topographic data, and satellite imagery.

Mean daily water temperature was then modelled along the accessible and potentially accessible rivers with a GAM using the day of the year and air temperature (ERA5-Land) as predictors. The model was calibrated using daily water temperature observations from the RivTemp Database and estimations from United States Geological Survey (USGS) Landsat thermal imagery. The goal is to evaluate the current thermal regime of Nunavik rivers by computing salmon thermal indicators and comparing them between salmon and non-salmon rivers. GAM models were then run under future climate scenarios to (1) project future river temperatures, (2) identify rivers likely to develop a thermal regime favourable to Atlantic salmon, and (3) assess the risk of thermal stress.

This study is one of the first to use remote sensing thermal infrared data from Landsat to predict the potential future water temperatures of Arctic and subarctic rivers, with the notable exception of Rincón et al. (2023), who modelled many river parameters for the Larch River in Nunavik.

2. Method and data

2.1. Study site

Nunavik is the territory above the 55th parallel north in the province of Quebec that stretches all the way to the Cape Wolstenholme near the 63rd parallel north (Fig. 1). The tree-

Table 1. Data used to identify the potential obstacles to the fish passage on Nunavik main river network.

Data source	Details
Literature – Salmonid studies – Environmental impact studies – River paddling river guide reports – Northern Quebec Photo Bank	Various literature sources which identify 16 obstacles for the fish and provide gathered photos for 30 potential obstacles.
Canadian Topographic Data (NRCan—CanVec) – Hydrographic obstacles – Contours lines	Hydrographic obstacles (i.e., falls and rapids) are identified in the CanVec data and the concentration of two or more contour lines indicates an important waterfall.
Imagery base maps – ESRI World Imagery – Google Earth Imagery	These high-resolution satellite base maps imagery help to confirm the presence of waterfalls, their morphology and to locate potential low water level sections.
Toponymy Commission of Quebec	When available, the official toponym was used to name the obstacles.

line crosses the territory at roughly 58° north, the southern part of Nunavik is in the forest tundra and open boreal forest compared to the higher latitude and elevation portions which are in the shrub tundra (Morneau et al. 2021). All analysis were conducted along the main river network defined, for the purpose of this study, as all waterbodies with a Strahler number equal or superior to six selected from the Géobase du Réseau Hydrographique du Quebec (MRNF 2019). These data allow for hydrological analysis and are an enhanced version of the original National Hydro Network from Natural Resources Canada. The main river network stretches over 27 500 km in Nunavik.

Historically, a first commercial salmon fishery was operated by the Hudson's Bay Company on the Koksoak, Whale and George rivers from the 1880s until the 1930s and it was reported that the stocks declined during that period (Dunbar 1952). Another commercial Atlantic salmon fishery started in 1961 on the Koksoak and Whale rivers and the populations appear to have been overfished, especially on the Koksoak River (Power and Le Jeune 1976; Le Jeune 1992). There is no more commercial fishing of Atlantic salmon in Nunavik, since it was banned in 2000, but Atlantic salmon is still harvested by Inuit and sports fishermen (April et al. 2023).

2.2. Identification of the current Atlantic salmon presence in Nunavik

A literature review was conducted to identify the current presence of Atlantic salmon in freshwater of the Ungava and Hudson watersheds using Google, Google Scholar, and Hydro Québec Environment & Communities Documentation Centre with the following keywords: "salmon", "salmo", "saumon", "ouananiche", "Nunavik", "Ungava", "Hudson", "Koksoak", "Melèze", "Larch", "Delay", "Du Gué", "George", "à la Baleine", "Whale", "Leaf", "aux Feuilles", and "Nastapoka". The literature review included not only peer-reviewed articles but also reports from governmental ministries and agencies.

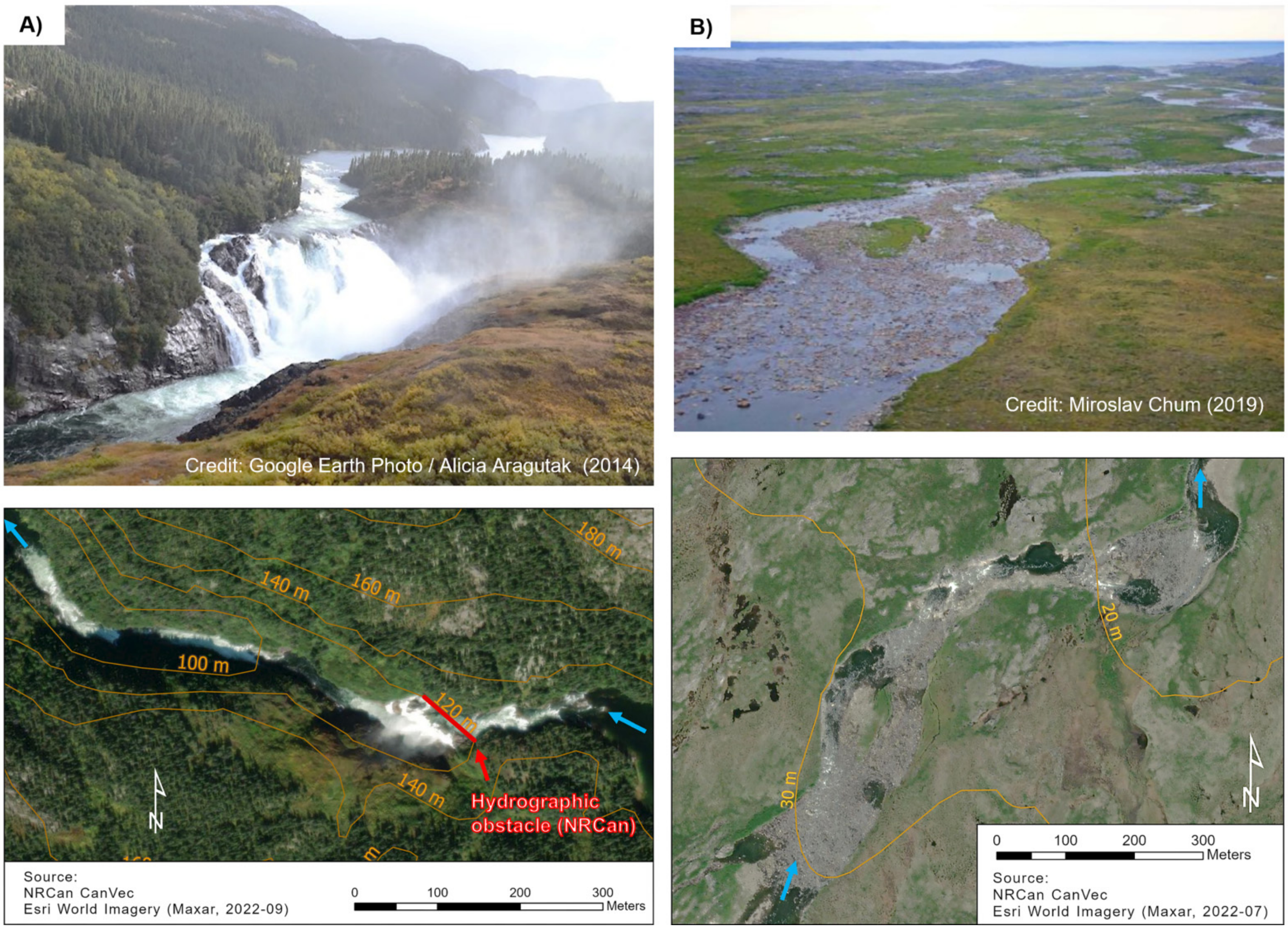
2.3. Identification of the accessible river network

For assessing the accessibility of the river network, it was assumed that there is no maximum distance that an Atlantic salmon can migrate upriver. Atlantic salmon spawners can migrate up an entire watershed to spawn as long as there are no obstacles, either permanent or temporary, of anthropogenic nature (e.g., dams, roads, and pollution) or natural origin (falls, shallow depths) restricting their movement (Thorstad et al. 2010). The longest reported Atlantic salmon migrations were up to 1000 km in the Elbe and Rhine rivers in Europe (Monnerjahn 2011; Wolter 2015) and some Atlantic salmon still migrate up to 920 km on the Loire-Allier System in France (Martin et al. 2012; Imbert et al. 2013). In North America, the longest migration was 645 km on the Connecticut River (Gephard 2008).

The Atlantic salmon's ability to pass an obstacle is highly variable and is determined by many factors: obstacle's height and slope, pool depth beneath the fall, flow, water level, water temperature, fish's size, and condition (Larinier et al. 1994; Thorstad et al. 2008, 2010). For instance, Beach (1984) observed an individual passing a 3.65 m fall, but a lower obstacle, with a less suitable morphology, could be harder to pass for the same fish (Thorstad et al. 2008). Therefore, in most cases the passability of an obstacle cannot be properly assessed without an on-site validation and even ichthyological inventory. Cases of identification of fish obstacles by remote sensing mostly relied on Lidar data (Kuiper et al. 2023) and such data in Nunavik are only available for the small territory of each community along the coast.

Potential obstacles were located by examining the full length of the main river network with the literature, by visual analysis of topographic data (NRCan 2019) and satellite base map imagery (Table 1). In the literature, experts identified 16 obstacles as barriers to salmonids. Additionally, photos of 30 obstacles or potential obstacles were found (including most of the 16 confirmed barriers), which helped in the assessment of their passability. Two types of obstacles were identified: waterfalls and low water level sections.

Fig. 2. Examples of the obstacles identification with pictures, topographic data and satellite basemap imagery: (A) impassable waterfalls on the Clearwater River (southern Hudson Bay); (B) potential impassable low water level section on the Curot River (southern Ungava Bay). Map sources: ESRI World Imagery, NRCan (2019); Coordinate system: NAD 1983 CSRS; Projection: Quebec Lambert Conformal Conic.



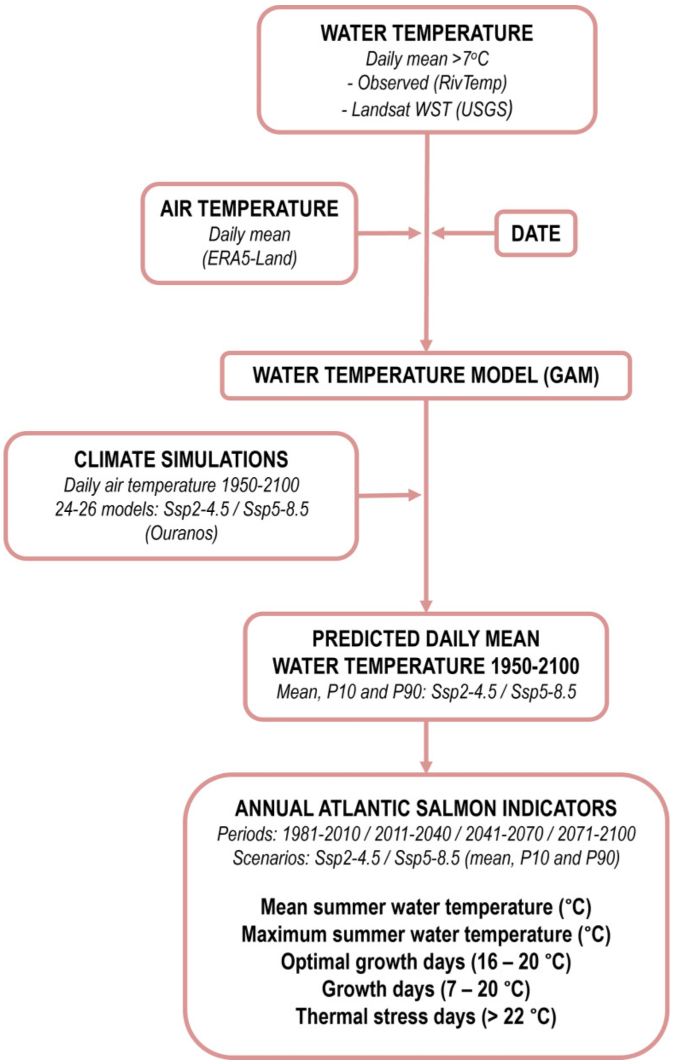
The waterfalls were identified where there was a hydrographic obstacle listed on the topographic data, concentration of the contour lines and big water movements visible on the satellite base map imagery (Fig. 2). Most identified waterfalls were classified as potential obstacles since their passability could not be confirmed with the available data. However, some obstacles were clearly impassable either because they were identified as such by previous on-site study ($n = 15$) or because the elevation gain was too high for the Atlantic salmon to swim up those falls which was defined as an abrupt waterfall of at least 10 m estimated with the contour lines. Obstacles identification was not pursued above those clearly impassable obstacles.

The low water level sections were identified with the ESRI World Imagery (available at: https://www.arcgis.com/home/item.html?id=10df2279f9684e4a9f6a7f08febac2a9) that has a very good resolution (up to 30 cm) for most of the Nunavik. Those sections were pinpointed where the riverbed was extensively visible with limited visible water (Fig. 2). Very low water level river sections in small rivers, which can block the migration of anadromous fish, have been reported by Inuit to be more frequent in recent years (Dubos et al. 2023*a*, 2023*b*). Therefore, it was decided to include the dry/shallow river sections that were observed with the satellite base map imagery as potential obstacles.

2.4. River temperature modelling

The water temperatures of the rivers were modelled with the nonparametric GAM along the main river network. The air temperature and the day of the year were the explanatory variables used to predict the water temperature (Fig. 3). The GAM, developed by Hastie and Tibshirani (1986), is a nonlinearregression model which can take into account the nonlinearity between the explanatory and dependent variables using smoothing functions. The GAM model can be expressed as shown in eq. 1, where *g* is a link function that relates the mean of the dependent variable to a set of explanatory variables, $E(y)$ is the expected value (mean) of the predicted variable, β_0 is equivalent to the intercept in linear regression, f_i $(i = 1 \ldots n)$ are the smoothing functions (here, cubic splines were used) of the explicative variables and ε is the estimated

Fig. 3. Workflow for modelling river temperature and computing annual Atlantic salmon thermal indicators under historical and future climate conditions. Water temperature is modelled as the response variable using air temperature and date as explanatory variables.



error:

$$g\left(E\left(y\right)\right)=\beta_0+f_1\left(x_1\right)+f_2\left(x_2\right)+\cdots+f_n\left(x_n\right)+\varepsilon \quad (1)$$

The execution of the models was carried out with the mgcv package (Wood 2011) in the R software (4.0.4). A Gaussian function was used for the link function to model river temperature because this function is more suitable than a sinusoidal function for modelling Quebec rivers (Daigle et al. 2019). The restricted maximum likelihood method was used for the smoothing function and the gamma parameter, where a higher value increases the smoothing, was set at 1.0, but the values of 1.4 and 2.0 were tested as well. The GAM model performance was evaluated with the root mean squared error (RMSE) and the number of data used in the model.

2.4.1. Water temperatures

Water temperature is the response variable in the model, and the GAM was fitted using both observed water temperature and estimated Landsat WST. Observed temperatures were obtained from the RivTemp network (Boyer et al. 2016). RivTemp is a database of water temperature time series gathered by various partners for rivers across Eastern Canada. On the Nunavik main river network, there are 59 sites all monitored by the Quebec Ministry of Forests, Wildlife and Parks with data that range from a few months to 6 years.

In addition to observed temperature, WST was estimated, through remote sensing, with the algorithm developed by Ermida et al. (2020) for the Google Earth Engine cloud computing platform (GEE). This algorithm is not specific to waterbodies; it can estimate the land surface temperatures (LST) globally from 1982 to the present but will hereafter be referred to only as WST. The algorithm utilizes the USGS thermal data from Landsat satellite's missions 4, 5, 7, 8, and 9[1] and the global Total Column Water Vapor (TCWS) data measured every 6 h by the National Center for Environmental Prediction and the National Center for Atmospheric Research. WST is estimated with the Statistical Mono-Window algorithm where *Tb* is the top of the atmosphere's radiance measured by the Landsat thermal sensors, ε is the emissivity of the studied object and *A*, *B*, and *C* are coefficients calculated for each sensor based on the TCWS at the time of the measurement:

$$\mathrm{WST}=A\frac{Tb}{\varepsilon}+B\frac{1}{\varepsilon}+C \quad (2)$$

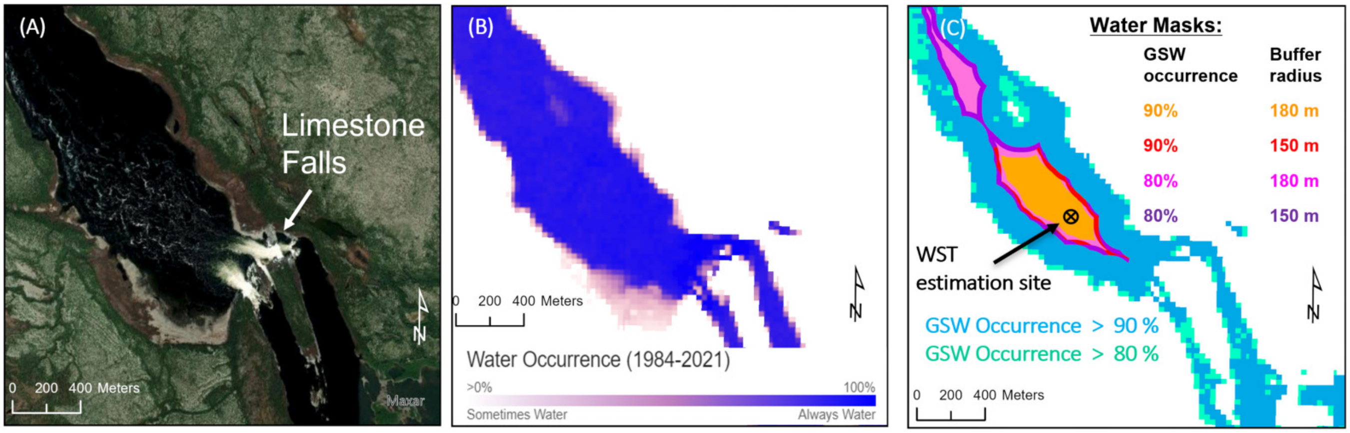
Since in this case the studied object is always water, the emissivity was fixed at 0.99 (Daigle et al. 2022; Dyba et al. 2022) instead of using, as in the original script, the emissivity from the advanced spaceborne thermal emission and reflection radiometer global emissivity database corrected with the normalized difference vegetation index of the scene when captured by the satellite. The recently released Landsat Collection 2 and Level 2 product from USGS (USGS 2021, 2022) with ready to use LST_L2 was not used because it was less performant than Ermida et al. (2020) algorithm to estimate waterbodies temperature and does not fully cover our study area.

The estimation of WST with Landsat thermal infrared data are limited to large rivers only. The original Landsat thermal infrared pixel resolutions are between 60 and 120 m and as the published thermal pixels by USGS are resampled to 30 m by cubic convolution it results in a thermal gradient perpendicular to the bank with mixed pixels of water and bank temperatures (Handcock et al. 2006; Martí-Cardona et al. 2019). Therefore, to avoid contamination with bank temperature, water temperature estimation sites must be on rivers with a minimum width of three times the original pixel resolution (Handcock et al. 2006). For this study, to have sufficient data, the estimation of WST was done only on rivers that are at least 300 m wide so the data from

[1] Table S1.

 Arctic Science 11: 1–23 (2025) | dx.doi.org/10.1139/as-2024-0084

Fig. 4. Example of the selection of a water surface temperature estimation site on the Caniapiscau River just below the Limestone Falls using the (A) ESRI World Base Map Imagery and (B) the global surface water product (Pekel et al. 2016) to create (C) water masks far enough from non-water pixels. Coordinate system: NAD 1983 CSRS; Projection: Quebec Lambert Conformal Conic.



Landsat 7, 8, and 9 can be used. However, most WST estimation sites were on rivers of at least 360 m wide so the data of all Landsat missions can be used. The selection of the site is very important for WST estimation to avoid land pixel contamination. To ensure that WST estimation sites are far enough at all times from non-water pixels, water masks were made from the occurrence dataset of the Global Surface Water v1.4 (GSW; a European Commission's Joint Research Centre product), that uses Landsat imagery to calculate the change of water extent globally from 1984 to 2021 (Pekel et al. 2016).

The sites for WST estimations were selected within the water mask polygons created by selecting the GSW pixels with a minimal occurrence of 80% which were vectorized and the water polygons were buffered internally with a radius of 150 and 180 m. The same procedure was done with pixels with an occurrence of 90% (Fig. 4). Most WST estimations sites, 53 sites over 78, were on rivers with a minimal width of 360 m and GSW occurrence of at least 90%.

The WST estimation sites were selected in river sections that were wide enough and, as much as possible, located in lotic environments, identified using the satellite base maps imagery and topographic data. The relatively high velocities and turbulence at these sites ensured that there is sufficient mixing of the water to ensure that the surface temperature is representative of the water column (Dugdale 2016). The same rationale was also applied in other studies that used Landsat WST in the region (Daigle et al. 2022; Rincón et al. 2023).

In Nunavik, the acquisition time of the Landsat imagery is between 10:30 and 12:30 (Eastern Daylight Time; UTC-04:00) depending on the missions and the site location. The observed temperatures measured at those times show the minimal deviation from the daily mean temperature (see "Results" section). Therefore, the Landsat WST is used in the GAM model as a proxy of the daily mean water temperature.

When possible, the WST were compared, independently for each Landsat mission, against the observed daily mean temperatures (T_{obs}) using the RMSE and biases:

$$\text{(3)} \quad \text{RMSE} = \sqrt{\frac{\sum (\text{WST} - T_{\text{obs}})^2}{N}}$$

$$\text{(4)} \quad \text{Bias} = \frac{\sum (\text{WST} - -T_{\text{obs}})}{N}$$

The WST estimations and observed temperatures were used in the GAM models either combined when possible or separately. When observed temperatures were used solely, only the stations with at least 5 years of data were kept. Only the water temperatures above 7 °C were kept for the GAM models to completely avoid the thawing season when ice can still be on the rivers and bias the WST estimations.

2.4.2. Air temperature

With the day of the year, air temperature is the other explanatory variable of the model. In Nunavik, air temperature observations are limited since there are not many weather stations across this vast territory. Most stations are relatively new, sparsely distributed and primarily located near the coasts. Consequently, the daily average air temperature from ERA5-Land was used to fit the GAM model.

The average air temperature was calculated from the minimum and maximum daily air values of the ERA5-Land product, extracted for each modelled site using Google Earth Engine. ERA5-Land, from the European Centre for Medium-Range Weather Forecasts, is an hourly global dataset (grid resolution of 0.1° × 0.1°) providing multiple variables for land applications and made from the reanalysis of the fifth generation of European Reanalysis Dataset (ERA5) which combines model data and observations (Muñoz-Sabater et al. 2021). It was chosen over Daymet, another gridded product (Thornton et al. 2022) since it performed better in estimating summer daily average air temperature in Nunavik (see Supplementary Material).

Table 2. List of the Atlantic salmon thermal indicators aggregated for each period (1981–2010, 2011–2040, 2041–2070, and 2071–2100).

Indicators	Rational
Days with optimal growth for salmon: Mean temperature between 16 and 20 °C	Evaluate the optimal growing condition for salmon.
Days with growth for salmon: Mean temperature between 7 and 22 °C	Quantify the growing season length for the salmon in a subarctic environment.
Days with thermal stress: Mean temperature > 22 °C	Verify the presence of thermal stress for salmon.
Mean summer water temperature (July–September)	Assess the general trend of the water temperature of the rivers.
Maximum summer water temperature (July–September)	Identify the potential maximum water temperature of the rivers.

2.4.3. Climate simulations

To predict historical and future water temperature, the GAM models were run with simulated air temperatures from Ouranos Ensemble of Bias-adjusted Simulations—Global models CMIP6 (ESPO-G6-R2) that cover North America at a 0.1° resolution from 1950 to 2100 (Lavoie et al. 2024). The simulated air temperatures were extracted for each site on the PAVICS platform (https://pavics.ouranos.ca). This ensemble corrects the bias of the global models with the detrended quantile mapping method (Cannon et al. 2015) and the regional deterministic reforecast system v2.1, a reanalysis product (Gasset et al. 2021) as the reference dataset. Utilizing reanalysis dataset for bias correction appears to be more accurate than interpolated gridded observation datasets for areas with sparse observation density (Essou et al. 2017; Carvalho et al. 2021), which is the case in Nunavik. The ESPO-G6-R2 dataset was chosen for this reason. Given the importance to capture the full spectrum of climate variability (Rahimpour Asenjan et al. 2023), all models (24–26 models depending on the emissions scenarios) were kept for this study. The “hot models”, as defined by Hausfather et al. (2022), were not excluded to ensure a comprehensive assessment of the potential water temperature variability. The mean, 10th percentile and 90th percentile of the daily model simulations were calculated for the medium (SSP2-4.5) and high (SSP5-8.5) emissions scenarios and were used with the GAM models to predict the water temperature for each site under different climate scenarios.

2.4.4. Thermal indicators for Atlantic salmon

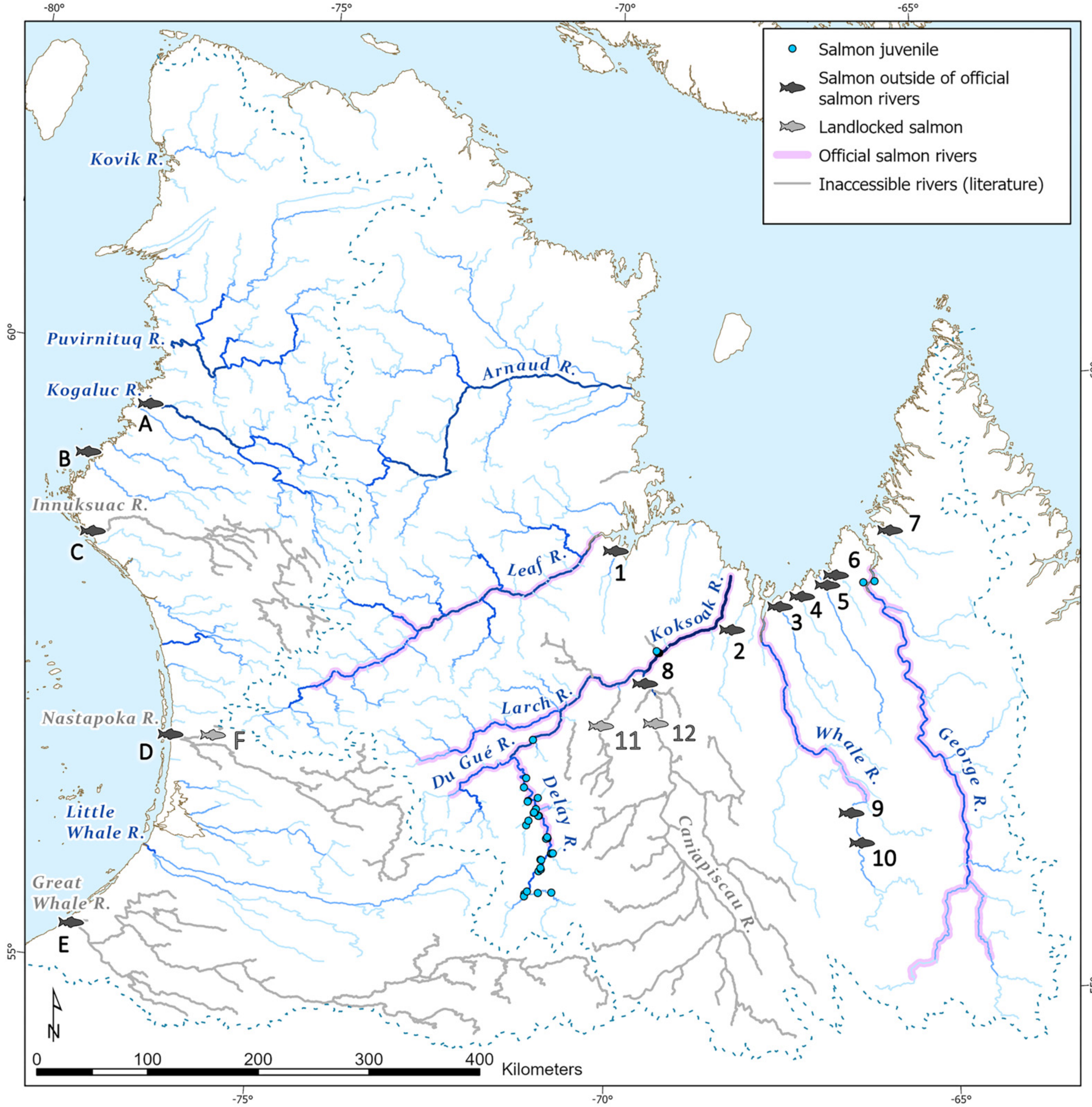
Yearly thermal indicators were computed from the predicted water temperatures to facilitate the comparison of the rivers across historical and future periods (Table 2). In the context of assessing the potential colonization of new subarctic rivers by Atlantic salmon, these indicators mostly focus on the minimum freshwater temperatures needed for the survival and growth of this species. Atlantic salmon eggs, juveniles, and smolts can survive in water temperature around 0 °C (Elliott and Elliott 2010) and juveniles acclimated to cold temperature have been reported to feed and sustain growth at temperature as low as 1 °C (Finstad et al. 2004; Elliott and Elliott 2010). Atlantic salmon can withstand and grow in very cold temperatures, but those temperatures are not relevant indicators for this study since these temperatures are too close to zero and the rivers would be covered by ice, which makes it impossible to estimate the temperature by remote sensing. Instead, the number of days with optimal temperatures for Atlantic salmon maximum growth, defined as water temperatures between 16 and 20 °C for Norwegian populations (Elliott and Elliott 2010), was selected as an indicator. Although these optimal growth temperatures were not measured for North American populations, they can still provide a good estimate of the growing season in the absence of local data. However, some salmon rivers in Nunavik barely reach those temperatures during the summer. Therefore, another indicator, the number of days with water temperature between 7 and 22 °C, was used to better represent the growing period in a cold climate. It is based on the only study (Jensen and Johnsen 1986) that looked at the growing season for Atlantic salmon related to water temperature in cold rivers in northern Norway: the growing season for Atlantic salmon was established at between 67 and 149 days with water temperature above 7 °C. Although, the focus was on the minimal temperature requirements for the establishment of Atlantic salmon populations, the number of days with primarily thermal stress, when the daily mean water temperature is above 22 °C (Elliott and Elliott 2010; Heggenes et al. 2021), was also evaluated to determine the presence of current and future thermal stress in Nunavik rivers. Additionally, two other indicators, the mean and maximum summer temperatures, were evaluated to quantify the general potential changes in the river temperatures.

3. Results

3.1. Atlantic salmon presence in Nunavik

The Atlantic salmon presence in Nunavik was extensively studied in the Koksoak River watershed (Fig. 5), particularly after the diversion in 1983 of a 36 900 km^2 area from the upper Caniapiscau River watershed, already inaccessible due to the Limestone Falls (Power 1958), to the La Grande hydroelectric complex (Roy and Messier 1989). Many spawning sites and reaches with juveniles have been documented (Côté et al. 1979; Belzile et al. 1982, 1984; Faunenord 2017) with juvenile present in the Delay River at more than 530 km from the mouth of the Koksoak River (Belzile et al. 1982; Faunenord 2017). Landlocked Atlantic salmon populations are also established above impassable waterfalls in Lake Aigneau and the Caniapiscau River (Power 1958).

Fig. 5. Map of Atlantic salmon presences in Nunavik with the inaccessible rivers identified in the literature. Map source: NRCan (2019) and MRNF (2019); Coordinate system: NAD 1983 CSRS; Projection: Quebec Lambert Conformal Conic.



The other salmon rivers were less extensively studied. Atlantic salmon were caught in Jeannin and Privert Lakes upstream of the official salmon river limit on the Whale River (Hydro-Québec 1978). An electrofishing campaign carried by the Quebec Ministry of Forests, Wildlife and Parks on some tributaries of the lower George River allowed to find juveniles in two streams (MFFP 2019—unpublished data). On the Leaf River, Lee and Power (1976) used rotenone to sample tributaries on the lower reach but found no salmon juvenile. Atlantic salmon has been reported occasionally in non-official salmon rivers of southern Ungava Bay (Table 3): all rivers between Kuujjuaq and Kangiqsualujjuaq (Dunbar and Hildebrand 1952), as well as in the Bérard River near Tasiujaq and the Koroc River near Kangiqsualujjuaq (Dubos et al. 2023*a*), but no spawning evidence was yet recorded in those rivers.

On the Hudson Bay watershed, Atlantic salmon is practically absent. Some individuals inhabit the brackish waters of the 1.4 km long estuary of the Nastapoka River at the foot of an impassable waterfall (Hydro-Québec 1993; Legendre 1990; Morin 1991). Landlocked Atlantic salmon are found above these falls in the river (Morin 1991; Hydro-Québec 1993) and in the upstream Kakiattualuk Lake where spawning has been

Table 3. List of adult Atlantic salmon presence outside of the official salmon rivers.

Watershed	ID Map	Watercourse	References
Ungava Bay	1	Bérard River	Dubos et al. (2023*a*); Mainguy et Beaupré (2019*b*)
	2	False River	Dunbar and Hildebrand (1952)
	3	Marralik River	Dunbar and Hildebrand (1952); Durkalec et al. (2020)
	4	Tuttutuuq River	Dunbar and Hildebrand (1952)
	5	Qurlutuq River	Dunbar and Hildebrand (1952)
	6	Lagrevé River	Dunbar and Hildebrand (1952)
	7	Koroc River	Cunjak et al. (1986); Dubos et al. (2023*a*)
	8	Caniapiscau River	Power (1958)
	9	Lake Jeannin	Hydro-Québec (1978)
	10	Lake Privert	Hydro-Québec (1978)
	11	Lake Aigneau[1]	Power (1958)
	12	Caniapiscau River[1]	Power (1958)
Hudson Bay	A	Kogaluc River	Legendre (1990)
	B	Mistake Bay	Morin (1991)
	C	Innuksuac River	Legendre (1990); Morin (1991); St-Pierre et al. (2010)
	D	Nastapoka River	Hydro-Québec (1993); Legendre (1990); Morin (1991)
	E	Great Whale River	Legendre (1990)
	F	Lake Kakiattualuk*	Hydro-Québec (1993)

Note: ID Map refers to the letter and number labels in Fig. 5.
*Landlocked Atlantic salmon

confirmed (Hydro-Québec 1993). The population in the estuary is not considered anadromous because although it has access to the sea, the analysis of the scales of these individuals does not show signs of smoltification or growth associated with marine migration (Hydro-Québec 1993; Legendre 1990). No spawning evidence was reported in the estuary. Therefore, the presence of Atlantic salmon in the estuary could be explained by individuals descending the river from upstream, which is the position of the Quebec Ministry of Forests, Wildlife and Parks about that population (April et al. 2023).

A specimen was also captured in the Kogaluc River and identified as non-anadromous following the analysis of its scales, which showed very close growth rings associated with a slow growth (Legendre 1990). Other captures have been recorded: in the Innuksuac River (Legendre 1990; Morin 1991; St-Pierre et al. 2010), at the mouth of the Great Whale River (Legendre 1990) and in Mistake Bay (Morin 1991). No scale analysis was performed on these specimens to determine if they were anadromous or not.

3.2. Accessible river network

A total of 192 obstacles were identified on the main river network with the topographic data, satellite basemap imagery and the literature (Fig. 6). In the literature, 15 obstacles to the fish movements were listed (Fig. 5): nine on the Koksoak watershed (Power 1958; Côté et al. 1979; Le Jeune 1981; Belzile et al. 1984), one waterfall on the Red Dog River near Aupaluk (Mainguy and Beaupré 2019*a*), three waterfalls on the Innuksuac River (St-Pierre et al. 2010), the Nastapoka Waterfall (Morin 1991) and the Qurlutuq Waterfall on the Great Whale River (Hydro-Québec 1993).

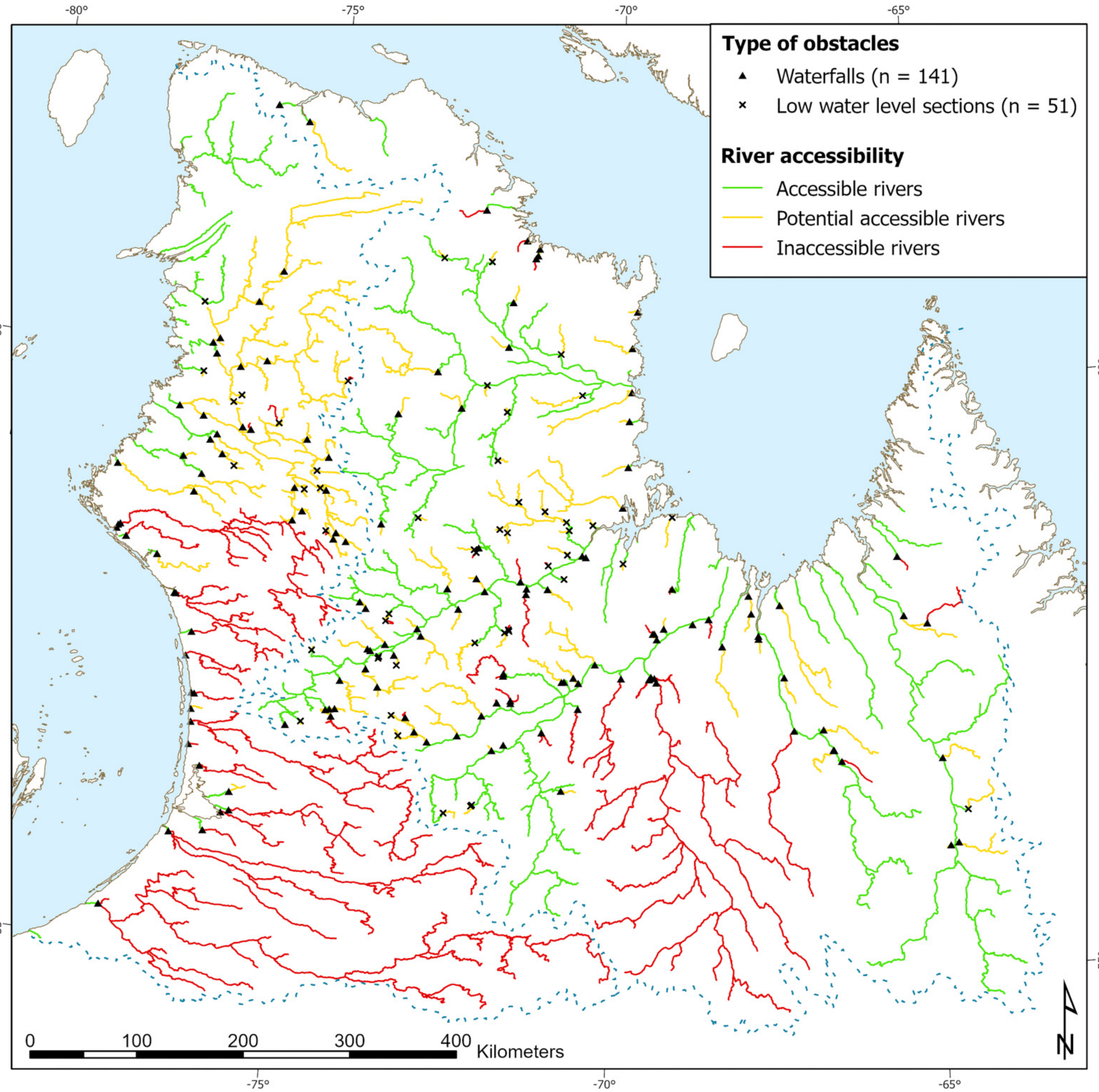
In total, waterfalls were the most recorded obstacles ($n = 141$) with 99 waterfalls identified as potentially impassable and 42 as impassable. All low water level sections ($n = 51$) were found in small streams only (Strahler number = 6): 43 sections were classified as potential obstacles and 8 as impassable because the riverbed was completely dry showing a complete discontinuity of the river network.

3.3. River diffluences

While assessing the rivers' accessibility, three river diffluences were found (Fig. 7). These are locations where the flow of a watercourse diverges into two separate watersheds. Those diffluences were found because of inaccuracies in the official data of the provincial hydrographic network and were validated with the satellite base map imagery. Although not part of the original objectives, these findings were included in this article due to the uniqueness of these features and their relevance in understanding the current distribution of Atlantic salmon in Nunavik.

One diffluence is between the watershed of the Great Whale and Little Whale rivers, in Southern Hudson Bay, that was noticed because the ordering of the Strahler number was inconsistent. Still on the Hudson Bay watershed, a portion of the flow of the Innuksuac River goes into the Kogaluc watershed which was found because of a mismatch between the river network and the watershed delimitation. For the same reason, another divergence was found between the upper Innuksuac River and the La Goudalie River, a tributary of the Leaf River, which its lower reach has the official salmon river status. Therefore, the Ungava Bay and Hudson Bay are interconnected by small channels linking lakes in the headwaters of the Leaf, Innuksuac and Kogaluc watersheds, forming a pathway of 750–780 km from one coast to the other.

Fig. 6. Map of the identified obstacles, waterfalls and low water level sections, on the Nunavik main river network (Strahler ≥ 6). Map source: NRCan (2019) and MRNF (2019); Coordinate system: NAD 1983 CSRS; Projection: Quebec Lambert Conformal Conic.



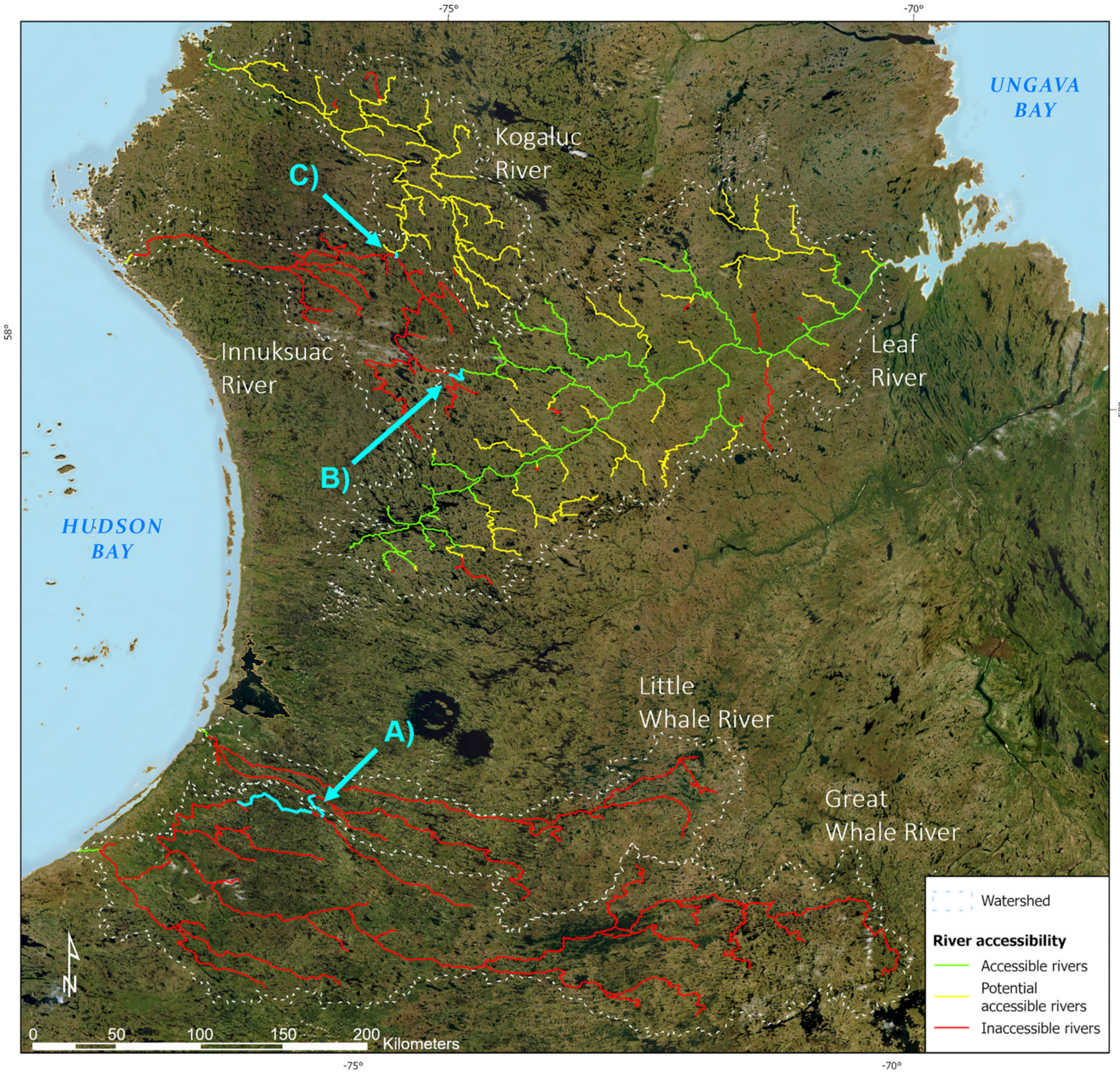
3.4. River temperature modelling

3.4.1. Validation of Landsat water surface temperature and GAM models

The hourly water temperature was compared to the daily mean temperature at 42 measurement sites in Nunavik in the summertime (1 July to 30 September). The lowest deviation of the hourly measurement to the daily mean is between 11:00 and noon (Fig. 8). The Landsat images are taken in Nunavik between 10:30 and 12:30 depending on the site location and the Landsat mission. During that period, the mean absolute deviation is below 0.4 °C and the percentile 95 of the absolute deviation is below 1.0 °C. Therefore, Landsat WST was used as a proxy of the daily mean water temperature.

Landsat WST estimations were possible nearby 18 RivTemp thermographs, because the rivers were large enough, so water temperature estimations and observations were combined for the GAM models. In addition, the WST estimations above 7 °C were compared, individually for each site and Landsat mission, against the observed daily mean water temperature (Table 4). The sites of the WST estimations were at a distance between 196 and 3015 m to the thermograph. The number of concomitant data are small for each site and mission ($n < 25$) due to the limited water temperature observa-

Fig. 7. Diffluences found in Nunavik: (A) an unnamed river split between the Great Whale and Little Whale rivers, (B) a portion of the upper Innuksuac River drain into the Leaf River, and (C) a portion of the Innuksuac River drain into the Kogaluc River. Map sources: ESRI World Imagery (Earthstar Geographics), NRCan (2019) and MRNF (2019); Coordinate system: NAD 1983 CSRS; Projection: Quebec Lambert Conformal Conic.



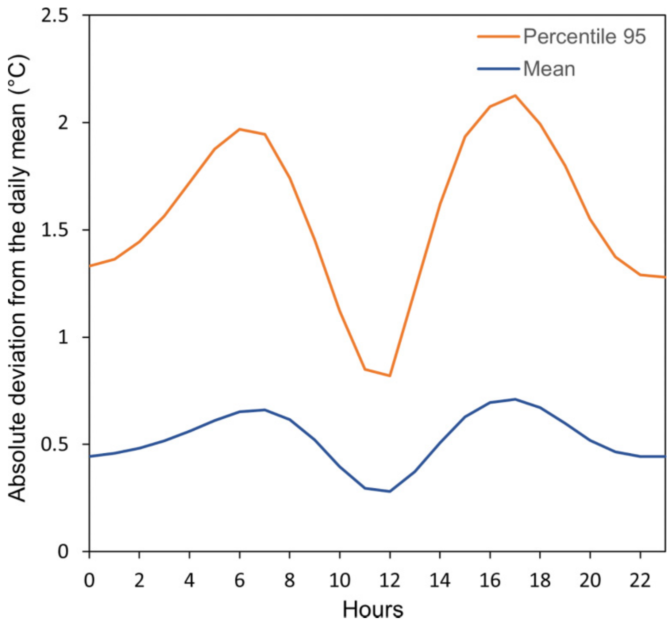
tions in the region. When considering all locations, the RMSE and bias for Landsat 7 WST are 1.84 and −0.61 °C. For Landsat 8 WST, the RMSE and bias are 1.60 and 0.03 °C. Only two sites have available observed temperatures to validate the most recent Landsat 9 mission. Given the recent water temperature observations, validation of the WST estimations by Landsat 5 was not possible and there was no WST estimation above 7 °C by Landsat 4.

On the accessible and potentially accessible rivers, the river temperature was modelled at 94 sites[2]. The GAM model performance was evaluated by comparing the RMSE value and the number of temperature measurements used in the model[3]. The models that used solely observed temperatures ($n = 16$) performed better with the lowest RMSE values: 1.14–1.69 °C. Those models are fitted with observations ($n = 278$–420) made over five and six summers. In comparison the models using only Landsat WST ($n = 60$) are fitted with fewer temperature measurements ($n = 101$–356) but over a longer period, between 25 and 42 summers depending on whether all Landsat missions were used for the larger reaches (>360 m) or only Landsat 7, 8, and 9 missions for the smaller reaches (>300 m). Those models show the highest RMSE values: 1.49–

[2] Figure S2.

[3] Table S2.

Fig. 8. Comparison of hourly water temperature absolute deviation from the daily mean water temperature measured based on 12 298 daily observations at 42 RivTemp locations between 1 July and 31 September.



2.20 °C. The models with combined observed temperatures and WST have the most temperature measurements ($n = 234$–678) for fitting the models, collected again between 25 and 42 summers, and the RMSE values are between: 1.28 and 2.10 °C.

3.4.2. Thermal indicators for salmon

The thermal indicators were calculated per period based on the daily water temperature predicted with the GAMs and the climate simulations. Two thermal indicators, mean summer temperature and growth days, were compared to visualize the potential evolution of the thermal regime at the 94 modelled sites from the historic period to the end-of-century, based on average climate simulations and considering the site location and the presence of Atlantic salmon (Fig. 9). The average increase of mean summer temperature for the 2071–2100 period would be between 1.44 °C (SSP2-4.5) and 2.47 °C (SSP5-8.5). When considering the results with the percentiles 10 and 90 of the climate models, mean summer temperature at each modelled site would increase between 0.48–2.45 °C (SSP2-4.5) and 0.90–4.13 °C (SSP5-8.5).

The yearly indicators averaged for the historic period (1981–2010) for the 36 sites located on salmon rivers with values varying depending on the sites and the percentile of the climate air simulations (Table 5): summer mean temperature (9.2–15.6 °C), maximum summer temperature (11.8–20.2 °C), growth days (81–132 days), optimal growth days (0–57 days), and thermal stress (0 day). The Koksoak River is the warmest river, with the highest indicators values, and the Leaf River is the coldest salmon river.

Under mean climate simulations, the lowest values predicted on a salmon river for the mean summer temperature and growth days indicators are respectively 10.9 °C and 101 days on the Leaf River. Sites that reach at least 11 °C as the mean summer temperature and have more than 100 growth days (temperature between 7–22 °C) were identified for each period and emissions scenarios (Fig. 10). That threshold for Atlantic salmon was used to assess, under mean climate simulations, which rivers reaches have or will have similar thermal regime to the coldest current salmon river reach evaluated herein.

For the historic period (1981–2010), other rivers than the official salmon rivers have thermal value above the chosen threshold for Atlantic salmon: four rivers on the southern Ungava Bay and three rivers on the Hudson Coast. In the Ungava watershed, all modelled sites on the southern rivers, from the Leaf River to the Koroc River, and the main reach of the Arnaud River would reach the threshold values as soon as 2041–2070 no matter the emissions scenarios. It includes the rivers that were reported to be visited by the Atlantic salmon already. For the 2071–2100 period, depending on the emissions scenario, only 1–3 additional rivers would reach those minimum values of 11 °C as mean summer temperature and 100 growth days. Some sites will remain colder than the actual coldest sites on the salmon rivers as they won't reach these values even with the highest emissions scenario (SSP5-8.5), which is the case for the northern tributaries of the Arnaud River. On the Hudson watershed, except for the northern most Kovik River and the upper watershed of the Purvirnituq River, under the SSP2-4.5 emissions scenario, all other monitored rivers would reach the Atlantic salmon threshold values by the 2071–2100 period.

By the end of the century, the number of days with optimal growth temperatures (16–20 °C) is projected to increase across most sites, depending on climate scenarios (Fig. 11). However, a few locations will still experience no days within the optimal growth temperatures range even under the warmest projection represented by the 90th percentile of the climate models using SSP5-8.5. For the current salmon rivers, under the mean climate simulations, the increase of the optimal growth temperature indicator will vary depending on the site and emissions scenario: between 0 and 43 days with an average of 18 days for SSP2-4.5 and between 3 and 63 days with an average of 34 days for SSP5-8.5. The results indicate that certain sites, under the same climate projection, could experience days with optimal growth temperatures without reaching the benchmark of 100 days above 7 °C. Conversely, other sites lack optimal growth conditions, but have at least 100 days above 7 °C. This pattern does not appear to be linked to the size of the rivers.

Historically (1981–2010), no thermal stress condition for the Atlantic salmon (daily mean temperature above 22 °C) was encountered on the studied sites. The projections of our models indicate that all sites would remain stress free under all future scenarios except under the warmest climate projection (P90, SSP5-8.5) where 25 sites would experience days with thermal stress mostly less than 5 days and up to 21 days[4]. Under this warmest projection, the maximum water temperature will vary between 13.5–23.6 °C with an average of 17.8 °C.

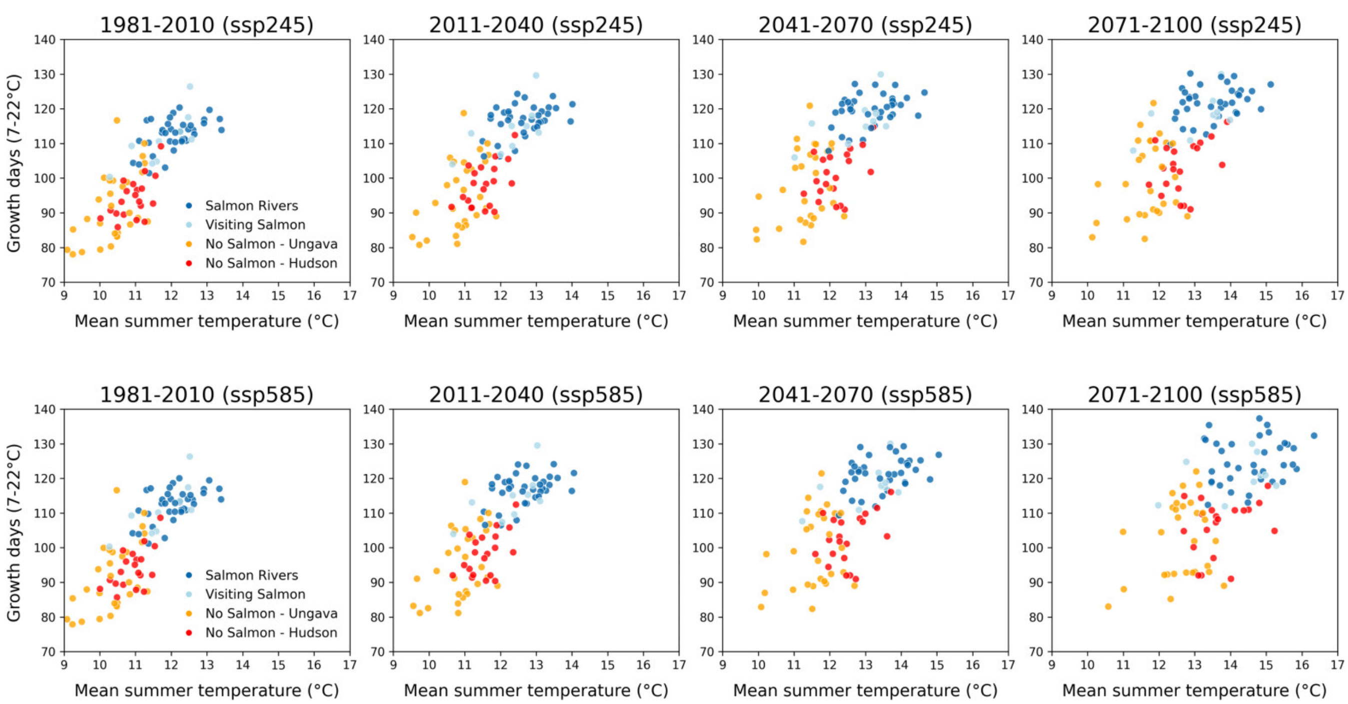
[4] Figure S3.

Table 4. Comparison of the spot Landsat Water Surface Temperatures (WST) estimations (>7 °C) against observed daily mean water temperature at 18 RivTemp sites.

Sites	Distance (m)	All Missions			Landsat 7			Landsat 8			Landsat 9		
		n	RMSE (°C)	Bias (°C)	n	RMSE (°C)	Bias (°C)	n	RMSE (°C)	Bias (°C)	n	RMSE (°C)	Bias (°C)
Riviere Koksoak_6	215	37	173	− 0.77	16	2.26	− 1.30	21	1.16	− 0.37	–	–	–
Riviere Koksoak_7	208	36	160	− 0.45	18	2.06	− 0.69	18	0.94	− 0.21	–	–	–
Riviere Koksoak_4	251	35	183	− 0.71	22	1.51	− 0.70	13	2.27	− 0.73	–	–	–
Puvirnituq_21 C	2198	33	132	− 0.11	9	1.25	− 0.04	24	1.35	− 0.13	–	–	–
Riviere Koksoak_8	196	33	113	− 0.24	14	1.49	− 0.47	19	0.75	− 0.07	–	–	–
Arnaud_Ar2	448	27	172	0.24	10	1.26	− 0.59	16	1.92	0.91	1	2.24	−2.24
Arnaud_Ar1	580	23	234	0.42	7	1.95	0.35	14	2.17	1.08	2	4.10	−3.88
Arnaud_Ar3	451	21	160	− 0.01	7	1.15	− 0.94	14	1.78	0.46	–	–	–
Passe Nallukallak_21Z	514	21	128	− 0.40	10	1.67	− 0.77	11	0.77	− 0.06	–	–	–
Puvirnituq_21 A	282	17	167	− 0.96	8	2.09	− 1.41	9	1.18	− 0.55	–	–	–
Aux Melezes	1625	16	146	− 0.02	7	1.92	− 0.69	9	0.96	0.51	–	–	–
Aux Feuilles_F2	759	14	132	0.04	10	1.19	− 0.32	4	1.61	0.93	–	–	
George River 2	285	13	174	− 1.40	4	1.57	− 1.54	9	1.81	− 1.34	–	–	–
Riviere Koksoak_3	265	8	419	3.16	6	3.91	2.65	2	4.94	4.71	–	–	–
Riviere Koksoak_5	408	7	216	− 1.00	3	2.49	− 2.28	4	1.87	− 0.03	–	–	–
Delay River	585	6	209	− 1.47	3	1.20	− 1.04	3	2.70	− 1.90	–	–	–
Riviere Nepihjee_0	3015	6	143	− 0.15	2	1.41	− 1.41	4	1.43	0.49	–	–	–
Delay River 3	939	3	081	− 0.42	3	0.81	− 0.42	–	–	–	–	–	–
All sites		356	173	− 0.28	159	1.84	− 0.61	194	1.60	0.03	3	3.59	−3.34

Note: The distance between the thermograph and the WST estimation site is given as well with the number of concomitant data (n). RMSE, root mean squared error.

Fig. 9. Evolution of two thermal indicators—growth days (7–22°C) and mean summer temperature (July–September)—for 94 sites over four periods for the average air temperature of the climate models with SSP2-4.5 and SSP5-8.5 scenarios.



Arctic Science 11: 1–23 (2025) | dx.doi.org/10.1139/as-2024-0084

Table 5. Average thermal indicators over the historical period (1981–2010) presenting the minimum, mean, and maximum value encountered at 36 sites located on the 4 salmon rivers with the percentile 10 (P10), 90 (P90) and mean (M) results of the climate simulations.

Climate simulations—indicators		Min	Mean	Max	Average per rivers: Koksoak ($n = 22$)	Whale ($n = 4$)	George ($n = 5$)	Leaf ($n = 5$)
P10	Mean summer temperature (°C)	9.2	10.6	11.9	10.8	10.5	10.7	9.5
	Maximum summer temperature (°C)	11.8	13.6	15.7	14.0	13.6	13.1	12.5
	Growth Days (7–22 °C)	81	96	109	98	92	98	86
	Optimal growth days (16–20 °C)	0	0	0	0	0	0	0
	Thermal stress days (>22 °C)	0	0	0	0	0	0	0
M	Mean summer temperature (°C)	10.9*	12.1	13.4	12.3	12.1	11.8	11.3
	Maximum summer temperature (°C)	13.3	15.1	17.5	15.5	15.2	14.4	14.3
	Growth Days (7–22 °C)	101*	113	120	115	109	112	108
	Optimal growth days (16–20 °C)	0	2	28	3	0	0	0
	Thermal stress days (>22 °C)	0	0	0	0	0	0	0
P90	Mean summer temperature (°C)	12.7	13.9	15.6	14.1	14.0	13.6	13.2
	Maximum summer temperature (°C)	15.8	17.5	20.2	17.6	18.0	17.4	16.9
	Growth Days (7–22 °C)	111	123	132	125	119	121	120
	Optimal growth days (16–20 °C)	0	27	57	31	27	21	11
	Thermal stress days (>22 °C)	0	0	0	0	0	0	0

Note: The average per river is also given.
*Indicators and values used as the threshold for salmon.

Fig. 10. Maps of the sites where water temperature was modelled (grey dots) and the sites expected to exceed 100 days above 7 °C with a mean summer temperature (July–September) of at least 11 °C (pink dots), shown by periods and emission scenarios. River accessibility assessment for Atlantic salmon: grey—inaccessible, orange—potentially accessible, green—accessible. Map source: NRCan (2019) and MRNF (2019); Coordinate system: NAD 1983 CSRS; Projection: Quebec Lambert Conformal Conic.

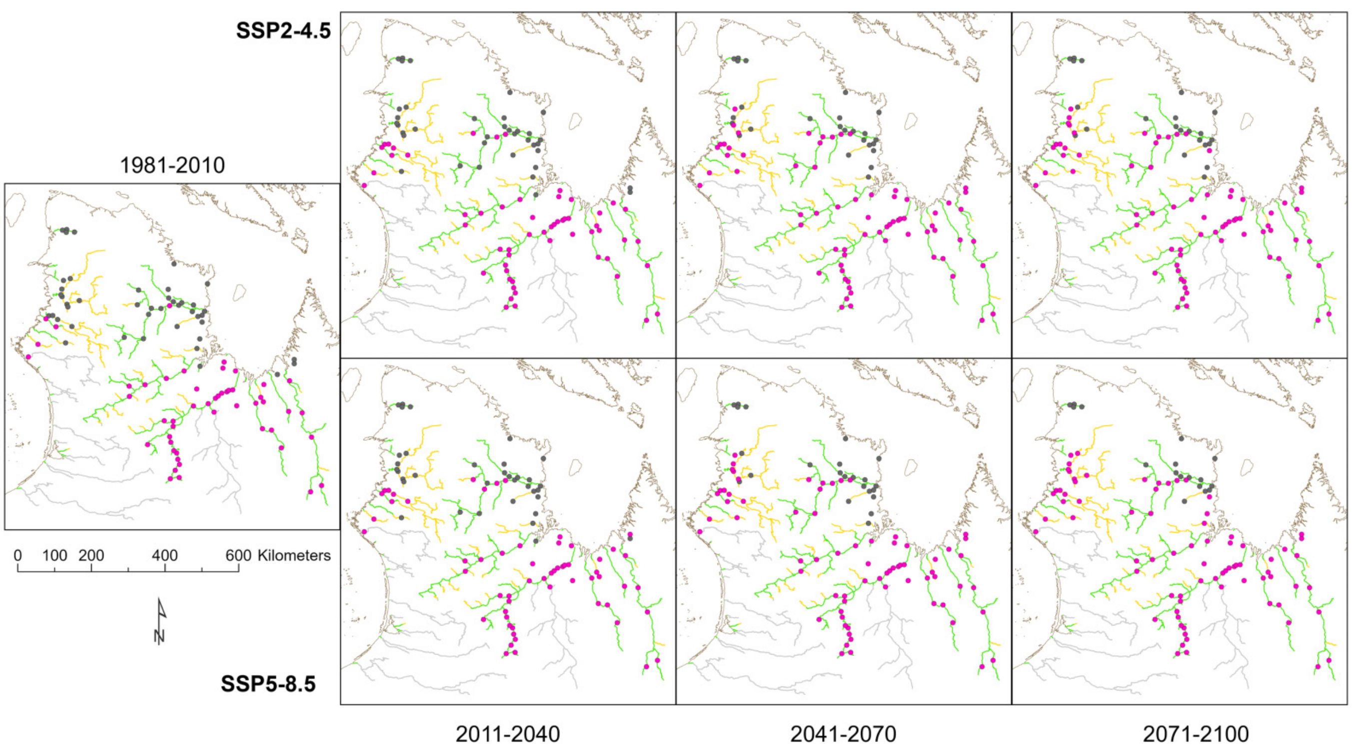
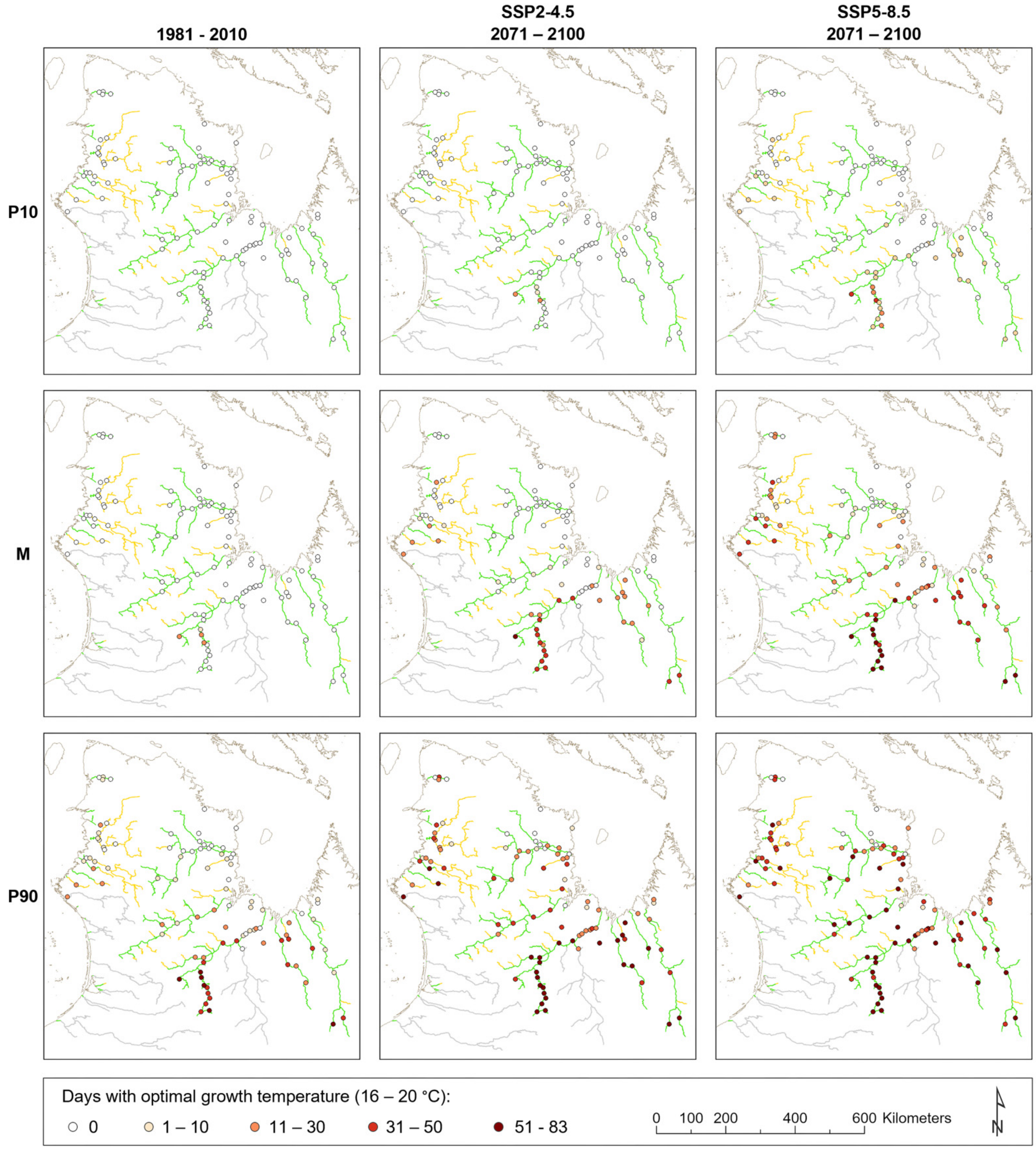


Fig. 11. Comparison of the optimal growth temperature indicator (days with temperature between 16 and 20 °C) for percentiles 10 (P10), 90 (P90), and mean (M) results of the climate simulations for the 1981–2010 period and the 2071–2100 period under the SSP2-4.5 and SSP5-8.5 emissions scenarios. River accessibility assessment for Atlantic salmon: grey—inaccessible, orange—potentially accessible, green—accessible. Map source: NRCan (2019) and MRNF (2019); Coordinate system: NAD 1983 CSRS; Projection: Quebec Lambert Conformal Conic.



4. Discussion

4.1. State of salmon presence in Nunavik

One aim of the study was to verify if the Atlantic salmon is present outside of the official salmon rivers in Nunavik. Our literature review provides the most up-to-date distribution of the species across the region and indicates that Atlantic salmon is present to some extent in seven other southern Ungava Bay rivers. There is no evidence of salmon spawning in those rivers, but at least some individuals visit them. It is possible that other rivers, draining into the Ungava Bay, are visited by salmon. To enhance the current assessment of salmon occurrences in Nunavik and monitor its potential colonization of new rivers, environmental DNA (eDNA) detection technique is simple and precise for detecting and monitoring fish species presence in waterbodies (Atkinson et al. 2018; Hernandez et al. 2020; Jacobsen et al. 2023). Combining eDNA with electrofishing surveys could help confirm population establishment. The use of Traditional Ecological Knowledge and community-base monitoring (Johnson et al. 2021; Heath and Rosengard 2022) in respect with Inuit Qaujimajatuqangit principles (Pedersen et al. 2020) would be highly valuable in future studies to refine the current assessment of Atlantic salmon presence in Nunavik and support monitoring efforts. Those methods could also be relevant for tracking the presence of pink salmon (*Oncorhynchus gorbuscha*) that have been reported in Ungava's rivers in recent years (Nicholl et al. 2021; April et al. 2023; Dubos et al. 2023*a*).

The official salmon rivers, the Leaf, Whale and George Rivers suffer from a lack of studies on the presence of salmon. By comparison, in the Koksoak River, the presence of juveniles, spawning sites and impassable obstacles have been identified in many reaches and tributaries, which are useful information for understanding those populations, their habitat uses in a subarctic climate and for fishery management. With the presence of juveniles on the Delay River confirmed at more than 530 km from the Ungava Bay (Belzile et al. 1982; Faunenord 2017), the Koksoak River appears to host the longest current freshwater migration of Atlantic salmon in North America.

On the Hudson Bay watershed, there is no evidence of anadromous Atlantic salmon since none of the scales analyzed displayed anadromous characteristics. The individuals in the estuary of the Nastapoka River are likely landlocked specimen coming from upstream where there is at least one establish landlocked Atlantic salmon population (April et al. 2023). It is probably the same situation for the Great Whale, Kogaluc and Innuksuac Rivers, where landlocked populations could be established in their upper watershed, which would explain the capture of Atlantic salmon in their estuary below impassable waterfalls.

Morin (1991) suggested that the few Atlantic salmon populations in the Hudson Bay watershed are remnants of the post-glacial colonization of the species at a time when the hydrographic basins of Ungava Bay could have been connected to those of Hudson Bay. His hypothesis is coherent with the facts that no salmon catches were recorded in the western side of Hudson Bay in Nunavut (Bilous and Dunmall 2020) and no mention in James Bay was found in the literature. Atlantic salmon is only present in rivers of the eastern Hudson Bay, whose watersheds are adjacent to the headwaters of Ungava salmon rivers. Furthermore, our study found a current linkage between the Ungava and Hudson watersheds so fish could migrate up the Leaf River watershed and reach the Innuksuac and Kogaluc Rivers where Atlantic salmon specimens have been captured historically. That route, technically possible, is long and the channel between the Innuksuac and Leaf watershed is small and could not be always accessible. Lastly, a recent genetic study on all Nunavik Atlantic salmon populations found that the Nastapoka River individuals are closer genetically to the salmon populations of the Delay and Du Gué Rivers, in the Koksoak watershed, than any other Ungava population which confirms the post-glacial inland migration hypothesis from the Ungava to the Hudson Bay (Carbonneau et al. 2024).

Morin (1991) raised the question of why Atlantic salmon have not colonized other rivers along the Hudson Coast following the post-glacial migration. That can be explained in part with our results, which show that most southern Hudson Bay rivers are simply not accessible to the salmon for colonization. Limitations include major waterfalls near their river mouth and although some rivers further north are accessible, they are generally too cold for the Atlantic salmon when compared to the thermal indicators of Ungava Bay salmon's rivers.

Even if the Atlantic salmon presence in the Hudson Bay rivers has been clarified with recent studies, including this one, it is still intriguing why there is no evidence of Atlantic salmon at sea visiting the Hudson Bay since it has been reported nearby, in the Hudson Strait and in the Foxe Basin just north of the Hudson Bay (Bilous and Dunmall 2020).

4.2. Nunavik rivers accessibility and connectivity

Although the technique for assessing the river accessibility was quite simple, it did allow confirming that most major Ungava rivers do not have obstacles that could prevent the migration of salmon. Therefore, the Atlantic salmon is not absent from the Nunavik northern rivers because of the inaccessibility of those rivers. The assessment also allowed to find that almost all southerner Hudson Bay rivers are inaccessible to the salmon due to a waterfall near their mouth as discussed in the previous section.

Following the deglaciation, the glacial isostatic adjustment is important in Nunavik with an elevation gain of 8–14 mm per year with the highest value in the Southern Hudson Bay region (Simon et al. 2016). It means that in the past, current inaccessible rivers could have been accessible to the salmon. At that rate, by the end of the century, the land could be 1 m higher in the south-west of Nunavik so potential obstacles could become impassable in the future. However, the potential sea level rise due to climate change could offset this isostatic adjustment. Under the pessimist scenario ssp5-8.5, the ICCP 6th Assessment Report of the Sea Level Projections indicates that the relative sea level would remain stable in the southern Hudson Bay by 2100 while increasing in the rest of Nunavik up to 0.6 m in eastern Ungava Bay (Garner et al. 2023). In the event of a low sea-level rise, the rivers identified as accessible are not expected to become inaccessible by 2100 due to the isostatic adjustment since no waterfalls were located on those rivers.

For the low water sections, some were identified as impassable because the creeks were completely dried out. That can be explained because the hydrographic network data used for the analysis in the region is derived from the Canadian National Topographic Data which has been produced, for most of Nunavik, from aerial photography from more than 40–50 years ago (NRCan 2004). Therefore, the hydrography could have changed quite substantially during that period. Future studies in Nunavik should look to produce their own hydrographic network from more modern remote sensing data.

The increase of the low water level sections in the Arctic and subarctic is a clear threat to the stream connectivity and fish movement (Bring et al. 2016; Koch et al. 2022; Dubos et al. 2023*a*, 2023*b*). The main reported cause of decreasing water levels in small Arctic streams is the increasing depth of the talik, the unfrozen soil under a waterbody, caused by the permafrost thawing, which increase the hyporheic drainage and can reduce the water level of lakes and rivers (Bring et al. 2016; Liljedahl et al. 2020; Koch et al. 2022). Dubos et al. (2023*a*) also suggested that due to the increase of riverine erosion caused by the thawing of permafrost (Rowland et al. 2010; Vincent et al. 2017) rivers are widening and becoming shallower. According to Del Vecchio et al. (2024), rivers are less channelled and shallower in the Arctic due to the frozen soil that limit the incision process, but with the permafrost thawing the incision process could increase resulting in more channelled stream in the future. The lowering water level of creeks in the Arctic is a phenomenon that should be more studied as it can impact fish populations and so the food security of Arctic communities.

4.3. Modelling river temperature with Landsat thermal imagery

The combined use of Landsat thermal imagery and GEE cloud computing platform is a real advance for studying the temperatures of remote rivers over time. Our results indicate that spot Landsat WST estimations can replace observed daily mean water temperatures in Nunavik. The acquisition time of Landsat imagery, near noon for the region, is right when there is the lowest deviation to the mean water temperature which was also the case for an American Midwest river (Tavares et al. 2020). Also, even with limited WST estimations due to cloud coverage and short ice-free season, the GAM models performed almost as well as with solely observed temperatures while allowing to monitor the temperature on more sites on more rivers. Appropriate site selection is crucial for accurate WST time series, because the original pixels of Landsat thermal bands are not made available, the published pixels are resampled, river water levels vary through a year and river morphology can change over 40 years. The water occurrence of the Global Surface Water product (Pekel et al. 2016) helped to select the sites for the WST estimations to ensure no contamination with land temperature, but the WST could still be biased by land temperature when the water level is particularly low. Therefore, there is a place for improving the site selection. Likely, research and applications of infrared remote sensing for studying waterbody temperatures are advancing rapidly with recent examples of an algorithm for the retrieval of WST on smaller rivers (Martí-Cardona et al. 2019) or a new machine learning algorithm for enhanced WST estimations (Dyba et al. 2022).

The use of percentiles 10 and 90 of all climate simulations models for medium and high emissions scenarios ensures that our analyses capture the potential variability of future river temperatures. However, the accuracy of those projections remains uncertain. For example, the river flow was not included in this study, but it can influence how the river temperatures will respond to climate change (St-Hilaire et al. 2021; Rivers-Moore and Dallas 2022; Seyedhashemi et al. 2022; Worrall et al. 2022). Additionally, while the GAM performs well with limited meteorological data, as a nonparametric statistical model, its predictions can be less accurate for future temperatures that deviate greatly from historical data (Benyahya et al. 2007). Future work should explore alternative modelling techniques and cross-validation with other studies, such as FutureStreams (Bosmans et al. 2022), to improve model robustness and confidence in water temperature projections. The projections would also have been more accurate if long-term observed air and water temperature data were available for the region. Hence, enhancing the network of water temperature monitoring and weather stations in the Arctic and subarctic would improve future modelling efforts.

4.4. Salmon potential colonization of Nunavik rivers

Colonization of new rivers by the Atlantic salmon could take times given that this species has a strong homing behaviour and most adult return to their natal river to spawn (Klemetsen et al. 2003; Thorstad et al. 2008). For instance, during a 2-year project on the Koksoak River, all salmon caught in the estuary came from the Koksoak watershed (Carbonneau et al. 2024). The opposite behaviour to homing is straying, which is the capability of anadromous fishes to visit or establish itself in a new river. It is an essential behaviour for the colonization of new rivers by the species and it can be induced by harsher conditions in the environment such as increased water temperature or competition (Nielsen et al. 2013; Birnie-Gauvin et al. 2019). Straying rates among wild Atlantic salmon populations has been estimated up to 4% (Pedersen et al. 2007) and 6% (Jonsson et al. 2003), but can exceed 20% in populations consisting of hatchery-reared or transplanted individuals (Keefer and Caudill 2014). In Nunavik, the presence of Atlantic salmon in other rivers in Nunavik and the fact that its presence is increasing (Dubos et al. 2023*a*) indicate that straying does occur and so colonization of new rivers is possible. Rivers closest to established populations have more chances to be colonized by the Atlantic salmon in response to climate change (Nielsen et al. 2013; Birnie-Gauvin et al. 2019).

Therefore, all rivers of southern Ungava Bay—from the Leaf River to the Koroc River—as well as the main reach of the Arnaud River, are the most likely to be colonized in Nunavik by Atlantic salmon by the end of the century. This is due to: (1) their proximity to existing populations (less than 200 km), (2) their accessibility, with no major barriers to upstream migration for adult salmon, and (3) projected water temperatures and growth periods will be suitable for Atlantic salmon regardless of the emissions scenario (SSP2-4.5 or SSP5-8.5).

Some rivers along the coast of Hudson Bay would reach suitable temperatures for Atlantic salmon, but they are less likely to be colonized quickly, as they are at a greater distance from established populations (at 1100 km or more) and their accessibility is uncertain, as many have potential obstacles that could not be properly assessed in our study. Those obstacles should be investigated in future research to gain a better understanding of which watersheds are accessible. Our colonization potential evaluation is not fully complete as many small rivers were not assessed, either due to the lack of observed water temperature data, their narrowness preventing Landsat WST estimation, or the large number of rivers that would have needed to be assessed. However, these rivers may also be potentially colonized by Atlantic salmon. The modelling of water temperature is insufficient in itself to determine the potential colonization of new rivers by Atlantic salmon as other parameters dictate its presence (Nielsen et al. 2013; Bilous and Dunmall 2020). For instance, in the southern Ungava Bay, some small rivers do not appear to be too cold for salmon, but they do not have established populations. In fact, winter warm refuge from groundwater input is important for the survival of salmonid species in Arctic rivers (Nielsen et al. 2013; Dunmall et al. 2016; Clawson et al. 2022). In regions with permafrost, large rivers have open talik with more groundwater exchange compared to small rivers, with closed talik, that only have thin and cold hyporheic drainage above the frozen permafrost (Fakhari et al. 2022). That could explain the presence of Atlantic salmon populations in Nunavik solely in large southern rivers, which have possibly better winter habitat for the salmon. Therefore, to enhance the assessment of potential Atlantic salmon colonization in Nunavik, a detailed evaluation of the quality of the available habitat should be conducted. Also, as the abundance of salmonids in rivers can be driven by temperature-related competition (Skoglund et al. 2024), the current interactions between Atlantic salmon with other anadromous salmonid species already cohabiting in Nunavik rivers, the Arctic char (*Salvelinus alpinus*) and brook trout (*Salvelinus fontinalis*) should be studied.

5. Conclusion

Even without in-depth habitat characterization, this study still employed a thorough approach to evaluate Atlantic salmon colonization potential of Nunavik Arctic and subarctic rivers emphasizing on understanding the current state of its presence in the region, the river thermal regime and accessibility. The Ungava Bay could be the first region to see Atlantic salmon expanding its range northward in response to climate change. This is supported by the presence of accessible rivers nearby established populations. It worth to underline the Arnaud River, the largest river draining into the Ungava Bay, will reach adequate temperature and is currently without a salmon population. This is supported by the presence of accessible rivers near established populations that are projected to reach adequate temperatures. Notably, this includes the Arnaud River, the largest river draining into the Ungava Bay, which currently does not host a salmon population. In summary, the warming of the rivers due to climate change would be beneficial for the Atlantic salmon in Nunavik not only in terms of colonization of new rivers, but also for the existing populations. Indeed, enhanced optimal growth conditions could lead to accelerated growth and earlier smoltification. Furthermore, our models predict limited thermal stress for the Atlantic salmon in Nunavik rivers by the end of the century. Foreseeable future threats to the current Ungava Atlantic salmon populations include the rise of sport and subsistence fishing due to the expansion of the Nunavik communities, invasive species and potential industrialization through activities like mining.

Acknowledgements

The authors would like to thank Anik Daigle for her valuable input on the use of Landsat Water Surface Temperature data to model river temperatures, as well as the reviewers—Collin Bouchard, Louis Moisan, and one anonymous reviewer—for their constructive comments and suggestions that helped improve this article.

Article information

History dates

Received: 16 December 2024
Accepted: 22 April 2025
Accepted manuscript online: 29 April 2025
Version of record online: 7 July 2025

Data availability

Data are available upon request.

Author information

Author ORCIDs

P. Poulin https://orcid.org/0009-0000-0196-175X

Author contributions

Conceptualization: PP, AS, NEB
Data curation: PP
Formal analysis: PP
Funding acquisition: AS
Methodology: PP, AS, CB, NEB
Project administration: AS

Software: PP, CB
Supervision: AS, NEB
Visualization: PP
Writing – original draft: PP
Writing – review & editing: PP, AS, CB, NEB

Competing interests

The authors declare there are no competing interests.

Funding information

This research was supported by The Foundation for Conservation of Atlantic Salmon (grant No. QC-2020-09).

Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/as-2024-0084.

References

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

Anderson, T. 1985. Rivers of Labrador. *In* Canadian special publication of fisheries and aquatic sciences 81. Department of Fisheries and Oceans, Fisheries Research Branch, Ottawa.

Andrews, D., and Coffey, J. 2009. Current Knowledge and Future Research Needs of Atlantic Salmon and Arctic Charr in Northern Labrador.

April, J., Bujold, V., Cauchon, V., Doucet-Caron, J., Gagnon, K., Guérard, M., et al. 2023. Information on the Atlantic Salmon (*Salmo sala r*) in Quebec for the preparation of the Second Status Report by the Committee on the Status of Endangered Wildlife in Canada. DFO Canadian Science Advisory Secretariat Research Document, 2023/008**,** 78.

Atkinson, S., Carlsson, J.E.L., Ball, B., Egan, D., Kelly-Quinn, M., Whelan, K., and Carlsson, J. 2018. A quantitative PCR-based environmental DNA assay for detecting Atlantic salmon (*Salmo salar* L.). Aquatic Conservation: Marine and Freshwater Ecosystem, **28**: 1238–1243. doi:10.1002/aqc.2931.

Beach, M. 1984. Fish pass design-criteria for the design and approval of fish passes and other structures to facilitate the passage of migratory fish in rivers.

Belzile, L., Haveur, G., Robitaille, J., and Shooner, G. 1982. Description de l'habitat des jeunes saumons de la rivière Delay, en Ungava et estimation des densités. Rapport conjoint SAGE/Gilles Shooner Inc. Doc. dactylo.

Belzile, L., Le Jeune, R., Levesque, F., Boudreault, A., and Shooner, G. 1984. Évaluation quantitative du potentiel salmonicole des principaux affluents inaccessibles du bassin Caniapiscau-Koksoak. Groupe d'étude conjoint Caniapiscau-Koksoak, Société d'énergie de la Baie-James.

Belzile, L., Robitaille, J., and Shooner, G. 1990. Synthèse des connaissances relatives à la biologie post-fraye du saumon atlantique (Salmo salar) en Ungava. Rapport technique canadien des sciences halieutiques et aquatiques N° 1738.

Benyahya, L., Caissie, D., St-Hilaire, A., Ouarda, T.B.M.J., and Bobée, B. 2007. A review of statistical water temperature models. Canadian Water Resource Journal, **32**: 179–192. doi:10.4296/cwrj3203179.

Bilous, M., and Dunmall, K. 2020. Atlantic salmon in the Canadian Arctic: potential dispersal, establishment, and interaction with Arctic char. Reviews in Fish Biology and Fisheries, **30**: 463–483. doi:10.1007/s11160-020-09610-2.

Birnie-Gauvin, K., Thorstad, E.B., and Aarestrup, K. 2019. Overlooked aspects of the *Salmo salar* and *Salmo trutta* lifecycles. Reviews in Fish Biolgy and Fisheries, **29**: 749–766. doi:10.1007/s11160-019-09575-x.

Bosmans, J., Wanders, N., Bierkens, M.F.P., Huijbregts, M.A.J., Schipper, A.M., and Barbarossa, V. 2022. FutureStreams, a global dataset of future streamflow and water temperature. Scientific Data, **9**: 307. doi:10.1038/s41597-022-01410-6. PMID: 35705555.

Botero-Acosta, A., Ficklin, D.L., Ehsani, N., and Knouft, J.H. 2022. Climate induced changes in streamflow and water temperature in basins across the Atlantic Coast of the United States: an opportunity for nature-based regional management. Journal of Hydrology: Regional Studies, **44**: 101202.

Boyer, C., St-Hilaire, A., Bergeron, N., Daigle, A., Curry, R., Caissie, D., and Gillis, C. 2016. RivTemp: a water temperature network for Atlantic salmon rivers in eastern Canada. Water News, **35**: 10–15.

Bring, A., Fedorova, I., Dibike, Y., Hinzman, L., Mård, J., Mernild, S.H., et al. 2016. Arctic terrestrial hydrology: a synthesis of processes, regional effects, and research challenges. Journal of Geophysical Research: Biogeoscience, **121**: 621–649. doi:10.1002/2015JG003131.

Brûlé, C. 2022. Occurrence de saumons atlantique (Salmo salar) estuariens dans la région de la baie d'Ungava (Nunavik, QC) confirmée par la chimie des otolithes et la morphologie des écailles. Université du Québec à Chicoutimi.

Caissie, D., El-Jabi, N., and Satish, M.G. 2001. Modelling of maximum daily water temperatures in a small stream using air temperatures. Journal of Hydrology, **251**: 14–28. doi:10.1016/S0022-1694(01)00427-9.

Cannon, A.J., Sobie, S.R., and Murdock, T.Q. 2015. Bias correction of GCM precipitation by quantile mapping: how well do methods preserve changes in quantiles and extremes? Journal of Climate, **28**: 6938–6959. doi:10.1175/JCLI-D-14-00754.1.

Carbonneau, A., April, J., Normandeau, E., Ferchaud, A.-L., Nadeau, V., and Bernatchez, L. 2024. Population genomics, life-history tactics, and mixed-stock subsistence fisheries in the northernmost American Atlantic salmon populations. Evolutionary Applications, **17**: e13654. doi:10.1111/eva.13654. PMID: 38405338.

Carvalho, D., Cardoso Pereira, S., and Rocha, A. 2021. Future surface temperatures over Europe according to CMIP6 climate projections: an analysis with original and bias-corrected data. Climate Change, **167**: 10. doi:10.1007/s10584-021-03159-0.

Chapman, B.B., Hulthén, K., Brodersen, J., Nilsson, P.A., Skov, C., Hansson, L.-A., and Brönmark, C. 2012. Partial migration in fishes: causes and consequences. Journal of Fish Biology, **81**: 456–478. doi:10.1111/j.1095-8649.2012.03342.x. PMID: 22803720.

Clawson, C.M., Falke, J.A., Bailey, L.L., Rose, J., Prakash, A., and Martin, A.E. 2022. High-resolution remote sensing and multistate occupancy estimation identify drivers of spawning site selection in fall chum salmon (*Oncorhynchus keta*) across a sub-arctic riverscape. Canadian Journal of Fisheries and Aquatic Sciences, **79**: 380–394. doi:10.1139/cjfas-2021-0013.

Cosewic 2011. Assessment and Status Report on the Atlantic Salmon, Salmo Salar, Nunavik Population, Labrador Population, Northeast Newfoundland Population, South Newfoundland Population, Southwest Newfoundland Population, Northwest Newfoundland Population, Québec Eastern North Shore Population, Québec Western North Shore Population, Anticosti Island Population, Inner St. Lawrence Population, Lake Ontario Population, Gaspé-southern Gulf of St. Lawrence Population, Eastern Cape Breton Population, Nova Scotia Southern Upland Population, Inner Bay of Fundy Population, Outer Bay of Fundy Population, in Canada, Committee on the Status of Endangered Wildlife in Canada.

Côté, Y., Hayeur, G., Le Jeune, R., and Shooner, G. 1979. Évaluation sommaire de potentiel salmonicole de la rivière Aux-Mélèzes. Groupe d'étude conjoint Caniapiscau-Koksoak, Société d'énergie de la Baie-James.

Cunjak, R. Power, G. and Barton, D. 1986. Reproductive habitat and behaviour of anadromous Arctic char (Salvelinus alpinus) in the Koroc River, Quebec. Naturaliste Canadien **113**(4): 383–387.

Daigle, A., Boyer, C., and Légaré, A. 2022. Modeling of the thermal regime of rivers subject to seasonal ice cover using data from different sources and temporal resolutions. Canadian Water Research Journal/Revue canadienne des ressources hydriques, 1–17.

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

Del Vecchio, J., Palucis, M.C., and Meyer, C.R. 2024. Permafrost extent sets drainage density in the Arctic. Proceedings of the National Academy of Science, **121**: e2307072120. doi:10.1073/pnas.2307072120.

Dubos, V., May, P., Gillis, C.-A., St-Hilaire, A., and Bergeron, N. 2023a. Nunavik anadromous Arctic char life histories, behaviour, and habitat use informed by both Inuit knowledge and western science: a year in Ungava Bay. Arctic Science, **0**: null.

Dubos, V., St-Hilaire, A., and Bergeron, N.E. 2023b. Fuzzy logic modelling of anadromous Arctic char spawning habitat from Nunavik Inuit knowledge. Ecological Modelling, **477**: 110262. doi:10.1016/j.ecolmodel.2022.110262.

Dugdale, S.J. 2016. A practitioner's guide to thermal infrared remote sensing of rivers and streams: recent advances, precautions and considerations. WIREs Water, **3**: 251–268. doi:10.1002/wat2.1135.

Dunbar, M., and Hildebrand, H. 1952. Contribution to the study of the fishes of Ungava Bay. Journal of Fisheries Research Board of Canada, **9**: 83–128. doi:10.1139/f52-005.

Dunbar, M.J. 1952. The Ungava bay problem. Arctic, **5**: 4–16. doi:10.14430/arctic3896.

Dunmall, K.M., Mochnacz, N.J., Zimmerman, C.E., Lean, C., and Reist, J.D. 2016. Using thermal limits to assess establishment of fish dispersing to high-latitude and high-elevation watersheds. Canadian Journal of Fisheries and Aquatic Sciences, **73**: 1750–1758. doi:10.1139/cjfas-2016-0051.

Durkalec, A., Basterfield, M., Jean-Gagnon, F., Kasudluak, P., and Breton-Honeyman, K. 2020. Inuit Knowledge of Beluga of Southern Ungava Bay and the Marralik (Mucalic) and Ungunniavik (Whale) River Estuaries. NMRWB Final report.

Dyba, K., Ermida, S., Ptak, M., Piekarczyk, J., and Sojka, M. 2022. Evaluation of methods for estimating lake surface water temperature using Landsat 8. Remote Sensing, **14**: 3839. doi:10.3390/rs14153839.

Elliott, J., and Elliott, J. 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**: 1793–1817. doi:10.1111/j.1095-8649.2010.02762.x. PMID: 21078091.

Ermida, S.L., Soares, P., Mantas, V., Göttsche, F.-M., and Trigo, I.F. 2020. Google earth engine open-source code for land surface temperature estimation from the landsat series. Remote Sensing, **12**: 1471. doi:10.3390/rs12091471.

Essou, G.R.C., Brissette, F., and Lucas-Picher, P. 2017. The use of reanalyses and gridded observations as weather input data for a hydrological model: comparison of performances of simulated river flows based on the density of weather stations. Journal of Hydrometeorology, **18**: 497–513. doi:10.1175/JHM-D-16-0088.1.

Fakhari, M., Raymond, J., Martel, R., Dugdale, S.J., and Bergeron, N. 2022. Identification of thermal refuges and water temperature patterns in salmonid-bearing subarctic rivers of Northern Quebec. Geographies, **2**: 528–548. doi:10.3390/geographies2030032.

Faunenord. 2017. Fréquentation du réseau Koksoak par le saumon atlantique (Salmo salar) de la baie d'Ungava, Nunavik: phase 2, validation terrain du sous-bassin de la rivière Delay.

Finstad, A.G., Næsje, T.F., and Forseth, T. 2004. Seasonal variation in the thermal performance of juvenile Atlantic salmon (*Salmo salar*). Freshwater Biology, **49**: 1459–1467. doi:10.1111/j.1365-2427.2004.01279.x.

Garner, G., Hermans, T.H.J., Kopp, R., Slangen, A., Edwards, T., Levermann, A., et al. 2023. IPCC AR6 WGI Sea Level Projections. World Data Center for Climate (WDCC) at DKRZ.

Gasset, N., Fortin, V., Dimitrijevic, M., Carrera, M., Bilodeau, B., Muncaster, R., et al. 2021. A 10 km North American precipitation and land-surface reanalysis based on the GEM atmospheric model. Hydrology and Earth System Sciences, **25**: 4917–4945. doi:10.5194/hess-25-4917-2021.

Geissinger, E.A., Van Leeuwen, T.E., Kelly, N., Pennell, C., Fitzsimmons, M.G., Duffy, S., et al. 2024. Salmonids in hot water: an unprecedented warm-water event in Labrador, a subarctic region of Canada. Fisheries Management and Ecology, **31**: e12710. doi:10.1111/fme.12710.

Gephard, S. 2008. Restoring Atlantic salmon (*Salmo salar*) to New England. Saving Biological Diversity: Balancing Protection of Endangered Species and Ecosystem, 75–84. doi:10.1007/978-0-387-09565-3.

Halverson, G.H., Lee, C.M., Hestir, E.L., Hulley, G.C., Cawse-Nicholson, K., Hook, S.J., et al. 2022. Decline in thermal habitat conditions for the endangered Delta smelt as seen from landsat satellites (1985–2019). Environmental Science & Technology. **56**: 185–193.

Handcock, R., Gillespie, A., Cherkauer, K., Kay, J., Burges, S., and Kampf, S. 2006. Accuracy and uncertainty of thermal-infrared remote sensing of stream temperatures at multiple spatial scales. Remote Sensing of Environment, **100**: 427–440. doi:10.1016/j.rse.2005.07.007.

Hastie, T., and Tibshirani, R. 1986. Generalized additive models. Statistical Science, **1**: 297–310, 14.

Hausfather, Z., Marvel, K., Schmidt, G.A., Nielsen-Gammon, J.W., and Zelinka, M. 2022. Climate simulations: recognize the "hot model' problem. Nature, **605**: 26–29. doi:10.1038/d41586-022-01192-2.

Heath, J., and Rosengard, S. 2022. SIKU: The Indigenous Knowledge Social Network, and tool for community-driven research. AGU Fall Meeting Abstracts, OS46A-03.

Hedeholm, R.B., Broberg, M., Nygaard, R., and Grønkjær, P. 2018. Population decline in the endemic Atlantic salmon (*Salmo salar*) in Kapisillit River, Greenland. Fisheries Management and Ecology, **25**: 392–399. doi:10.1111/fme.12306.

Hedger, R.D., Sundt-Hansen, L.E., Forseth, T., Ugedal, O., Diserud, O.H., Kvambekk, Å.S., and Finstad, A.G. 2013. Predicting climate change effects on subarctic–Arctic populations of Atlantic salmon (*Salmo salar*). Canadian Journal of Fisheries and Aquatic Sciences, **70**: 159–168. doi:10.1139/cjfas-2012-0205.

Heggenes, J., Stickler, M., Alfredsen, K., Brittain, J.E., Adeva-Bustos, A., and Huusko, A. 2021. Hydropower-driven thermal changes, biological responses and mitigating measures in northern river systems. River Research and Applications, **37**: 743–765. doi:10.1002/rra.3788.

Hernandez, C., Bougas, B., Perreault-Payette, A., Simard, A., Côté, G., and Bernatchez, L. 2020. 60 specific eDNA qPCR assays to detect invasive, threatened, and exploited freshwater vertebrates and invertebrates in Eastern Canada. Environmental DNA, **2**: 373–386. doi:10.1002/edn3.89.

Hydro-Québec. 1978. Projet Ungava. Rivières George, à la Baleine et Arnaud. Études préliminaires d'environnement. Synthèse des données recueillies. Milieu aquatique. Direction Environnement Ecologie Biophysique, Montréal.

Hydro-Québec. 1993. Rapport d'avant-projet. Partie 2: Complexe hydroélectrique. Tome 2: Description du milieu. Volume 2: Milieu naturel marin.: Complexe Grande-Baleine.

Imbert, H., Martin, P., Rancon, J., Graffin, V., and Dufour, S. 2013. Evidence of late migrant smolts of Atlantic salmon (*Salmo salar*) in the Loire-Allier System, France. Cybium, **37**: 5–14.

Jacobsen, M.W., Nygaard, R., Hansen, B.K., Broberg, M., Hansen, M.M., Hedeholm, R., and Nielsen, E.E. 2023. Observing the Arctic: a comparison of environmental DNA (eDNA) and electrofishing for monitoring Arctic char and Atlantic salmon. Environmental DNA, **5**: 782–795. doi:10.1002/edn3.442.

Jensen, A.J., and Johnsen, B.O. 1986. Different adaptation strategies of Atlantic salmon (*Salmo salar*) populations to extreme climates with special reference to some cold Norwegian rivers. Canadian Journal of Fisheries and Aquatic Sciences, **43**: 980–984. doi:10.1139/f86-120.

Johnson, N., Druckenmiller, M.L., Danielsen, F., and Pulsifer, P.L. 2021. The use of digital platforms for community-based monitoring. Bioscience, **71**: 452–466. doi:10.1093/biosci/biaa162.

Jonsson, B., and 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**: 2381–2447. doi:10.1111/j.1095-8649.2009.02380.x.

Jonsson, B., Jonsson, N., and Hansen, L.P. 2003. Atlantic salmon straying from the River Imsa. Journal of Fish Biology, **62**: 641–657. doi:10.1046/j.1095-8649.2003.00053.x.

Keefer, M.L., and Caudill, C.C. 2014. Homing and straying by anadromous salmonids: a review of mechanisms and rates. Reviews in Fish Biology and Fisheries, **24**: 333–368. doi:10.1007/s11160-013-9334-6.

Klemetsen, A., Amundsen, P.-A., Dempson, J.B., Jonsson, B., Jonsson, N., O'connell, M.F., and Mortensen, E. 2003. Atlantic salmon *Salmo salar* L., brown trout *Salmo trutta* L. and Arctic charr *Salvelinus alpinus* (L.): a review of aspects of their life histories. Ecology of Freshwater Fish, **12**: 1–59. doi:10.1034/j.1600-0633.2003.00010.x.

Koch, J.C., Sjöberg, Y., O'donnell, J.A., Carey, M.P., Sullivan, P.F., and Terskaia, A. 2022. Sensitivity of headwater streamflow to thawing permafrost and vegetation change in a warming Arctic. Environmental Research Letters, **17**: 044074. doi:10.1088/1748-9326/ac5f2d.

Kuiper, S.D., Coops, N.C., Hinch, S.G., and White, J.C. 2023. Advances in remote sensing of freshwater fish habitat: a systematic review to identify current approaches, strengths and challenges. Fish Fisheries, **24**: 829–847. doi:10.1111/faf.12772.

Laanaya, F., St-Hilaire, A., and Gloaguen, E. 2017. Water temperature modelling: comparison between the generalized additive model, logistic, residuals regression and linear regression models. Hydrological Sciences Journal, **62**: 1078–1093. doi:10.1080/02626667.2016.1246799.

Lamarins, A., Carlson, S.M., and Buoro, M. 2024. Dispersal and gene flow in anadromous salmonids: a systematic review. Ecology of Freshwater Fish, **33**: e12811. doi:10.1111/eff.12811.

Larinier, M., Porcher, J.P., Travade, F., and Gosset, C. 1994. Passes a poissons. Expertise, conception des ouvrages de franchissement.

Lavoie, J., Bourgault, P., Smith, T.J., Logan, T., Leduc, M., Caron, L.-P., et al. 2024. An ensemble of bias-adjusted CMIP6 climate simulations based on a high-resolution North American reanalysis. Scientific Data, **11**: 64. doi:10.1038/s41597-023-02855-z.

Le Jeune, R. 1981. Appréciation sommaire de la valeur piscicole des affluents du fleuve Koksoak, entre la chute Calcaire et la municipalité de Kuujjuaq. Groupe d'étude conjoint Caniapiscau-Koksoak, Société d'énergie de la Baie-James. p. 44

Le Jeune, R. 1992. Développement des pêches du Québec nordique: état des ressources Entente auxiliaire Canada-Québec sur le développement des pêches. Volet III—Québec nordique. Groupe Environnement Shooner inc, Québec.

Lee, R., and Power, G. 1976. Atlantic salmon (*Salmo salar*) of the Leaf river, Ungava Bay. Journal of Fisheries Research Board of Canada, **33**: 2616–2621. doi:10.1139/f76-311.

Legendre, V. 1990. Âge des ouananiches d'après leurs écailles, fleuve Nastapoka, estuaire, Québec, à la baie d'Hudson. Montréal. Éditions Groupe Environnement Shooner inc., Québec.

Liljedahl, A.K., Timling, I., Frost, G.V., and Daanen, R.P. 2020. Arctic riparian shrub expansion indicates a shift from streams gaining water to those that lose flow. Communications Earth & Environment, **1**: 50.

Mainguy, J., and Beaupré, L. 2019a. Establishment of a reference state for Arctic charr populations in Aupaluk. Ministère des Forêts, de la Faune et des Parcs, Direction de l'expertise sur la faune aquatique and Direction de la gestion de la faune du Nord-du-Québec, Québec.

Mainguy, J., and Beaupré, L. 2019b. Establishment of a reference state for the Arctic charr population of the Bérard River in Tasiujaq. Ministère des Forêts, de la Faune et des Parcs, Direction de l'expertise sur la faune aquatique and Direction de la gestion de la faune du Nord-du-Québec, Québec.

Maoiléidigh, N.Ó., White, J., Hansen, L.P., Jacobsen, J.A., Potter, T., Russell, I., et al. 2018. Fifty years of marine tag recoveries from Atlantic salmon. ICES Cooperative Research Reports (CRR).

Martí-Cardona, B., Prats, J., and Niclòs, R. 2019. Enhancing the retrieval of stream surface temperature from Landsat data. Remote Sensing of Environment, **224**: 182–191. doi:10.1016/j.rse.2019.02.007.

Martin, P., Rancon, J., Segura, G., Laffont, J., Boeuf, G., and Dufour, S. 2012. Experimental study of the influence of photoperiod and temperature on the swimming behaviour of hatchery-reared Atlantic salmon (*Salmo salar* L.) smolts. Aquaculture, **362-363**: 200–208. doi:10.1016/j.aquaculture.2011.11.047.

Monnerjahn, U. 2011. Atlantic Salmon (*Salmo salar* L.) re-introduction in Germany: a status report on national programmes and activities. Journal of Applied Ichthyology, **27**: 33–40. doi:10.1111/j.1439-0426.2011.01849.x.

Morin, R. 1991. Atlantic salmon (*Salmo salar*) in the lower Nastapoka River, Quebec: distribution and origins of salmon in eastern Hudson Bay. Canadian Journal of Zoology, **69**: 1674–1681. doi:10.1139/z91-232.

Morneau, C., Couillard, P.-L., Laflamme, J., and Major, M. 2021. Classification écologique du territoire québécois, Direction des inventaires forestiers.

Mrnf. 2018. Découpages administratifs Données Québec—Ministère des Ressources naturelles et des Forêts.

Mrnf. 2019. Géobase du réseau hydrographique du Québec (GRHQ). Données Québec—Ministère des ressources naturelles et des forêts.

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., et al. 2021. ERA5-Land: a state-of-the-art global reanalysis dataset for land applications. Earth System Science Data, **13**: 4349–4383. doi:10.5194/essd-13-4349-2021.

Nicholl, D.G.M., Harris, L.N., Loewen, T., May, P., Tran, L., Akeeagok, R., et al. 2021. Noteworthy occurrences among six marine species documented with community engagement in the Canadian Arctic. Animal Migration, **8**: 74–83. doi:10.1515/ami-2020-0113.

Nielsen, J.L., Ruggerone, G.T., and Zimmerman, C.E. 2013. Adaptive strategies and life history characteristics in a warming climate: salmon in the Arctic? Environmental Biology of Fishes, **96**: 1187–1226. doi:10.1007/s10641-012-0082-6.

NRCAN. 2004. National Hydro Network, Canada, Level 1 Product Specifications Sherbrooke: Centre for Topographic Information.

NRCAN. 2019. Topographic Data of Canada—CanVec Series. Open Government—Natural Resources Canada, Canada.

Ouarda, T.B.M.J., Charron, C., and St-Hilaire, A. 2022. Regional estimation of river water temperature at ungauged locations. Journal of Hydrology, **17**: 100133. doi:10.1016/j.hydroa.2022.100133.

Pedersen, C., Otokiak, M., Koonoo, I., Milton, J., Maktar, E., Anaviapik, A., et al. 2020. ScIQ: an invitation and recommendations to combine science and Inuit Qaujimajatuqangit for meaningful engagement of Inuit communities in research. Arctic Science, **6**: 326–339. doi:10.1139/as-2020-0015.

Pedersen, S., Rasmussen, G., Nielsen, E.E., Karlsson, L., and Nyberg, P. 2007. Straying of Atlantic salmon, *Salmo salar*, from delayed and coastal releases in the Baltic Sea, with special focus on the Swedish west coast. Fisheries Management and Ecology, **14**: 21–32. doi:10.1111/j.1365-2400.2006.00520.x.

Pekel, J.F., Cottam, A., Gorelick, N., and Belward, A.S. 2016. High-resolution mapping of global surface water and its long-term changes. Nature, **540**: 418–422. doi:10.1038/nature20584.

Power, G. 1958. The evolution of the freshwater races of the Atlantic salmon (*Salmo salar* L.) in eastern North America. Arctic, **11**: 86–92. doi:10.14430/arctic3735.

Power, G. 1981. Stock characteristics and catches of Atlantic salmon (*Salmo salar*) in Quebec, and Newfoundland and Labrador in relation to environmental variables. Canadian Journal of Fisheries and Aquatic Sciences, **38**: 1601–1611. doi:10.1139/f81-210.

Power, G., and Le Jeune, R. 1976. Le potentiel de pêche du Nouveau-Québec. Cahiers de géographie du Québec, **20**: 409–428. doi:10.7202/021328ar.

Power, M., Reist, J.D., and Dempson, J.B. 2008. Fish in high-latitude Arctic lakes. Polar Lakes Rivers, 249–267. doi:10.1093/acprof:oso/9780199213887.001.0001.

Rahimpour Asenjan, M., Brissette, F., Martel, J.L., and Arsenault, R. 2023. Understanding the influence of "hot" models in climate impact studies: a hydrological perspective. Hydrology and Earth System Sciences, **27**: 4355–4367. doi:10.5194/hess-27-4355-2023.

Rincón, E., St-Hilaire, A., Bergeron, N.E., and Dugdale, S.J. 2023. Combining Landsat TIR-imagery data and ERA5 reanalysis information with different calibration strategies to improve simulations of streamflow and river temperature in the Canadian Subarctic. Hydrological Processes, **37**: e15008. doi:10.1002/hyp.15008.

Rivers-Moore, N.A., and Dallas, H.F. 2022. A spatial freshwater thermal resilience landscape for informing conservation planning and climate change adaptation strategies. Aquatic Conservation: Marine and Freshwater Ecosystem, **32**: 832–842. doi:10.1002/aqc.3812.

Robitaille, J., Côté, Y., Hayeur, G., and Shooner, ETG. 1984. Particularités de la reproduction du saumon atlantique (Salmo salar) dans une partie du réseau Koksoak, en Ungava, Pêches et océans.

Robitaille, J.A., Côté, Y., Shooner, G., and Hayeur, G. 1986. Growth and maturation patterns of Atlantic salmon, *Salmo salar*, in the Koksoak River, Ungava, Quebec. Canadian Special Publication of Fisheries and Aquatic Sciences, **89**: 62–69.

Rowland, J.C., Jones, C.E., Altmann, G., Bryan, R., Crosby, B.T., Hinzman, L.D., et al. 2010. Arctic landscapes in transition: responses to thawing Permafrost. Eos, Transactions American Geophysical Union, **91**: 229–230. doi:10.1029/2010EO260001.

Roy, D., and Messier, D. 1989. A review of the effects of water transfers in the La Grande hydroelectric complex (Quebec, Canada). Regulated Rivers: Research Management, **4**: 299–316.

Salonius, P.O. 1973. Barriers to range extension of Atlantic and Pacific salmon in arctic North America. Arctic, 112–122.

Santiago, J.M., Alonso, C., Garcia De Jalon, D., Solana-Gutiérrez, J., and Muñoz-Mas, R. 2020. Effects of climate change on the life stages of stream-dwelling brown trout (*Salmo trutta* Linnaeus, 1758) at the rear edge of their native distribution range. Ecohydrology, **13**: e2241. doi:10.1002/eco.2241.

Seyedhashemi, H., Vidal, J.-P., Diamond, J.S., Thiéry, D., Monteil, C., Hendrickx, F., et al. 2022. Regional, multi-decadal analysis on the Loire River basin reveals that stream temperature increases faster than air temperature. Hydrology and Earth System Sciences, **26**: 2583–2603. doi:10.5194/hess-26-2583-2022.

Simon, K., James, T., Henton, J., and Dyke, A. 2016. A glacial isostatic adjustment model for the central and northern Laurentide Ice Sheet based on relative sea level and GPS measurements. Geophysical Journal International, **205**: 1618–1636. doi:10.1093/gji/ggw103.

Skoglund, H., Forseth, T., and Einum, S. 2024. Among-river pattern in relative abundance of two salmonid fishes reflects temperature-dependent competition. Freshwater Biology, **69**: 1057–1068, doi:10.1111/fwb.14289.

St-Hilaire, A., Caissie, D., Bergeron, N.E., Ouarda, T.B., and Boyer, C. 2021. Climate change and extreme river temperature. *In* Climate Change and Extreme Events. Elsevier.

St-Hilaire, A., Oyinlola, M.A., Rincón, E., and Ferchichi, H. 2023. Six decades of research on river temperature in Canada. Canadian Water Research Journal/ Revue canadienne des ressources hydriques, **48**: 450–474. doi:10.1080/07011784.2023.2283241.

St-Pierre, S., Mcneil, E., and Bouillon, M. 2010. Projet d'aménagement hydroélectrique Innavik, rivière Inukjuak. Rapport d'étude d'impact sur l'environnement et le milieu humain. RSW inc, Montréal.

Tavares, M.H., Cunha, A.H.F., Motta-Marques, D., Ruhoff, A.L., Fragoso, C.R., et al. 2020. Derivation of consistent, continuous daily river temperature data series by combining remote sensing and water temperature models. Remote Sensing of Environment, **241**: 111721. doi:10.1016/j.rse.2020.111721.

Thornton, M.M., Shrestha, R., Wei, Y., Thornton, P.E., Kao, S.C., and Wilson, B.E. 2022. Daymet: daily surface weather data on a 1-km grid for North America, Version 4 R1. ORNL Distributed Active Archive Center.

Thorstad, E., Whoriskey, F., Rikardsen, A., and Aarestrup, K. 2010. Aquatic nomads: the life and migrations of the Atlantic Salmon.

Thorstad, E.B., Økland, F., Aarestrup, K., and Heggberget, T.G. 2008. Factors affecting the within-river spawning migration of Atlantic salmon, with emphasis on human impacts. Reviews of Fish Biology and Fisheries, **18**: 345–371. doi:10.1007/s11160-007-9076-4.

USGS. 2021. Landsat 4-7 Collection 2 (C2) Level 2 Science Product (L2SP) Guide. United States Geological Survey, Asheville, NC, USA. pp. 1–44.

USGS. 2022. Landsat 8-9 Collection 2 (C2) Level 2 Science Product (L2SP) Guide. United States Geological Survey, Asheville, NC, USA. pp. 1–42.

Van Vliet, M.T.H., Franssen, W.H.P., Yearsley, J.R., Ludwig, F., Haddeland, I., Lettenmaier, D.P., and Kabat, P. 2013. Global river discharge and water temperature under climate change. Global Environmental Change, **23**: 450–464. doi:10.1016/j.gloenvcha.2012.11.002.

Vanhellemont, Q. 2020. Automated water surface temperature retrieval from Landsat 8/TIRS. Remote Sensing of Environment, **237**: 111518. doi:10.1016/j.rse.2019.111518.

Vincent, W.F., Lemay, M., and Allard, M. 2017. Arctic permafrost landscapes in transition: towards an integrated Earth system approach. Arctic Science, **3**: 39–64. doi:10.1139/as-2016-0027.

Wolter, C. 2015. Historic catches, abundance, and decline of Atlantic salmon *Salmo salar* in the River Elbe. Aquatic Science, **77**: 367–380. doi:10.1007/s00027-014-0372-5.

Wood, S.N. 2011. Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. Journal of Royal Statistical Society Series B: Statistical Methodology, **73**: 3–36. doi:10.1111/j.1467-9868.2010.00749.x.

Worrall, F., Howden, N.J., Burt, T.P., and Hannah, D.M. 2022. River water temperature demonstrates resistance to long-term air temperature change. Hydrological Processes, **36**: e14732. doi:10.1002/hyp.14732.