Thermal habitat: Understanding stream temperature and thermal classifications

Information Report IR-18

Science and Research Branch
Ministry of Natural Resources and Forestry

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Thermal habitat: Understanding stream temperature and thermal classifications

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Cover photo: An example of the complexity of classifying stream temperature: The water in this side channel of the Agawa River mainstem was about 16 °C, cooled by groundwater coming from the streambank, while the main channel was 23 °C.

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Summary

Water temperature influences the distribution and abundance of species, water quality, nutrient and ice dynamics, and the metabolic activity, growth, timing of migration, and spawning events of fishes. A good understanding of the thermal regime of streams and rivers is needed for effective resource management. This report stemmed from a lack of understanding and considerable confusion about stream temperature dynamics, classification, and species thermal biology.

Stream temperatures vary in time and space, making it difficult to develop a single classification. Similarly, fishes can be found in a range of water temperatures and have physiological and behavioural coping strategies that allow them to tolerate temperatures warmer and colder than they prefer, making their classification (e.g., coldwater fish) difficult. Traditionally, stream temperature has been classified into cold-, cool-, and warmwater types. More recently, several authors have developed additional classes. The threshold temperatures used (e.g., <19 °C) are not standardized and vary within and among regions in North America.

Fish are highly dependent on water temperature to maintain important biochemical, physiological, and life history processes. Although fish have well defined preferences, they can inhabit a range of temperatures, several degrees warmer than their preferred temperature. How much warmer depends on the duration of exposure, availability of food resources, and their ability to find cooler patches of water. Although fish may seek cooler water during periods of high temperatures in summer, for the remaining 8 to 11 months of the year temperature is not limiting and they can move freely in the stream network or into neighbouring lakes. In winter, fishes may move into warmer water to find overwintering habitat. In areas without barriers, fish can exploit the spatial variation in stream temperatures across the network to maximize fitness.

Most predictive models produce an average stream temperature value providing minimal understanding of annual variability. A more robust approach uses multiple years of field data to create probabilities for given temperatures. Alternatively, model predictions can be made using multiple years of historical air temperature data to provide multiple estimates for a stream reach. These estimates can be used to make a distribution to obtain probabilities for different temperature thresholds (e.g., probability of an average July water temperature greater than 18.5 °C). This measure of uncertainty is useful in making decisions about thermal class membership.

Stream temperature is just one of several determinants of brook trout (*Salvelinus fontinalis*) presence/absence and the aquatic ecosystem classification developed for Ontario does not directly predict brook trout occupancy. To protect brook trout, a model is needed that directly predicts their occurrence. This information can be used to strategically prioritize field activities (e.g., electrofishing, eDNA) to focus on streams with higher probabilities of occurrence to confirm presence/absence of fishes. In the absence of such maps, field crews are less able to make efficient use of their limited time.

Sommaire

Habitat thermique : comprendre la température des cours d'eau et les classifications thermiques

La température de l'eau influe sur sa qualité, la distribution et l'abondance des espèces, les variations des nutriments et des glaces, ainsi que sur l'activité métabolique, la croissance et les périodes de migration et de frai des poissons. La gestion efficace des ressources passe par une bonne compréhension du régime thermique des ruisseaux et des rivières. Ce rapport vise à pallier l'incompréhension de la dynamique de la température des cours d'eau, de la classification et de la biologie thermique des espèces, et à dissiper toute confusion.

Les températures des cours d'eau varient dans le temps et dans l'espace, ce qui complique l'élaboration d'une classification unique. De même, les poissons peuvent vivre dans une fourchette de températures. Ils adoptent des stratégies d'adaptation physiologique et comportementale qui leur permettent de tolérer des températures plus chaudes ou plus froides que celles qu'ils préfèrent. Leur classification devient donc difficile (p. ex. poissons d'eaux froides). Traditionnellement, la température des cours d'eau est classée selon qu'il s'agit d'eaux froides, tempérées ou chaudes. Plusieurs auteurs ont récemment proposé des catégories supplémentaires. Les températures seuils utilisées (p. ex. < 19 °C) ne sont pas normalisées; elles varient d'une région à l'autre en Amérique du Nord.

Chez les poissons, le maintien d'importants processus biochimiques, physiologiques et biologiques dépend grandement de la température de l'eau. Bien qu'ils aient des préférences bien définies, les poissons peuvent vivre dans une échelle de température, souvent à une température plus chaude de plusieurs degrés que leur température favorite. Le degré de chaleur toléré dépend de la durée de l'exposition, de la disponibilité des ressources alimentaires et de la capacité à trouver des zones d'eau plus froide. Si, en été, les poissons recherchent l'eau plus fraîche pendant les grandes chaleurs, la température n'est pas un facteur limitant les déplacements; pendant les 8 à 11 mois restants de l'année, ils circulent librement dans le réseau hydrographique ou dans les lacs voisins. En hiver, les poissons peuvent se déplacer dans des eaux plus chaudes pour trouver un habitat d'hivernage. Dans les zones sans barrières, les poissons peuvent exploiter la variation spatiale de la température de l'eau du réseau hydrographique pour maximiser leur forme physique.

La plupart des modèles prédictifs fournissent une température moyenne du cours d'eau qui ne reflète pas vraiment sa variabilité annuelle. Une approche plus fiable consiste à analyser des données de terrain recueillies sur plusieurs années pour calculer les probabilités d'une température donnée. Par ailleurs, des modèles de prévisions peuvent produire de multiples estimations d'un tronçon de cours d'eau par l'analyse de données historiques de plusieurs années sur la température de l'air. Ces estimations peuvent servir à établir une distribution en vue de calculer des probabilités pour différents seuils de température (p. ex. la probabilité que la température moyenne de l'eau en juillet soit supérieure à 18,5 °C). Cette mesure d'incertitude s'avère utile pour prendre des décisions relatives à la stratification thermique.

La température des cours d'eau n'est qu'un des nombreux déterminants de la présence ou de l'absence de l'omble de fontaine (*Salvelinus fontinalis*); la classification des écosystèmes aquatiques établie pour l'Ontario ne prédit pas directement les zones d'occupation de ce poisson. Pour protéger l'omble de fontaine, il faut un modèle qui prédit directement sa présence. L'utilisation de ces renseignements facilite l'établissement d'un ordre de priorité stratégique des activités sur le terrain (p. ex. pêche à l'électricité, tests d'ADN) permettant ainsi de se concentrer sur les cours d'eau dont la probabilité d'occurrence est plus élevée afin de confirmer la présence ou non de poissons. En l'absence de telles cartes, les équipes sur le terrain parviennent moins efficacement à rentabiliser le temps limité dont elles disposent.

Contents

Introduction

Thermal regime is of central importance in sustaining the ecological integrity of aquatic ecosystems. Water temperature has been described as the abiotic master factor for fishes (Brett 1971, Hannah and Garner 2015) and even as an ecological resource (Magnuson et al. 1979). Water temperature influences the distribution and abundance of species; water quality, nutrient, and ice dynamics; and the metabolic activity, growth, timing of migration, and spawning events of fishes (Caissie 2006; Prowse 2001a, b). Therefore, a good understanding of the thermal regime of streams and rivers is needed for effective fisheries management and environmental impact assessments.

This report stemmed from a lack of understanding of stream temperature dynamics, thermal classification, and species thermal biology in Ontario. Common questions include: Is this a cold water stream? How far up or downstream can we say it is coldwater? Is this a brook trout (*Salvelinus fontinalis*) stream? As such, here we provide i) an appreciation of the spatial and temporal variability of water temperature, ii) clarity about how to think about stream water temperatures and their classification, iii) an understanding of the thermal preferences and tolerances of fishes, and iv) information about how fish exploit water temperatures in streams to maximize growth and survival. In many examples, we use brook trout to illustrate points, but the principles apply to other fish species.

Spatial and temporal variability of stream temperature

Water temperature is a function of many variables that can be grouped into 4 categories: (i) atmospheric conditions, (ii) topography, (iii) stream discharge, and (iv) streambed characteristics (Caissie 2006). The main factors driving stream temperature vary geographically. At coarse spatial scales, elevation, latitude (air temperature), and groundwater are important. For example, in southern Appalachia, Tennessee, small streams at high elevations, where air temperatures are cool, have colder water and are suitable for species such as brook trout that are not found in warmer streams at lower elevations. In southern Ontario, groundwater is the source of cold water, whereas in northern Ontario, high latitudes and associated cooler air temperatures along with a short growing season keep water temperatures low. Because stream temperatures vary spatially (longitudinally, laterally, and by depth) and temporally (from year to year (inter-annually), seasonally, and daily), it is difficult to identify the main driving factors or to develop a single classification system.

For any given stream reach, water temperatures in summer rise and fall by several degrees daily (e.g., from 16 °C in the early morning to 22 °C by late afternoon; Figure 1A). In the early morning, brook trout would experience temperatures close to their thermal optimum for growth (15 °C). As the day progresses, water temperatures increase by 1 to 2 °C per hour and by late afternoon the trout would feel hot, decrease their activity, and search for cooler water near cold tributaries, at the bottom of deep pools, and in areas of hyporheic flow discharges near the streambed. Movements to find cooler waters are small or local in scale. So even though the main flow of a stream might be warm (>21 °C), trout can use small cold water inputs

to find reprieve. The hyporheic zone is water beneath and alongside a stream bed where shallow groundwater mixes with surface water.

During a cold year, perhaps during a La Niña summer, temperatures in this same river may never exceed 19 °C and brook trout would not feel the need to find cooler water (Figure 1B). During a hot year, or El Niño period, the water temperature may exceed 19 °C continuously during the day and night (20–26 °C) for several weeks (Figure 1C). Brook trout would need to move to cold headwater reaches or find thermal refugia such as upwellings, springs, or seeps where they can thermoregulate. These movements would likely be at larger scale in a stream network, illustrating the need for stream connectivity and problems with barriers that prevent longitudinal movement.

Obviously, a stream with an average July temperature of 14 °C is not likely to exceed 19–20 °C, so would be categorized as very cold. This level of certainty also exists for a stream with an average July temperature of 26 °C, which would be categorized as warm. Most streams, however, will not be this extreme. Many will be near the thermal class boundaries, requiring additional information about the level of certainty about their thermal class (e.g., probability).

Although fish may seek cooler water during periods of high temperatures during summer, for the remaining 8 to 11 months of the year temperature is not limiting and they can move freely in the stream network or into neighbouring lakes. This is particularly true for migratory salmon and trout that use Great Lake tributaries during the cooler months from September to June. In winter fishes may move into overwintering habitats to find warmer water and avoid anchor (submerged and attached to bottom) and frazil, pool-filling, ice accumulations.

In addition to temporal variability in an individual stream reach, thermal habitat differs from year to year across a stream network (Figure 2). The spatial variation in stream temperatures across the network can be exploited by brook trout if they can move. In the absence of barriers such as waterfalls and improperly installed culverts, brook trout can move to access a wider range of habitats in cold years (Figure 2B) and seek refuge in cool headwater regions in hot years (Figure 2C). In some years, preferred thermal habitat (blue streams segments) is widely available (Figure 2B) whereas in hot years it might be restricted to small patches of cold groundwater or headwaters (Figure 2C). Small-scale variations in water temperature also occur near cold water sources such as springs (Figure 3).

These scenarios illustrate the spatial and temporal complexities of thermal habitat and that classifying a stream's temperature using a single value is an oversimplification. Similarly, a single temperature criterion for fish presence/absence is also unrealistic. Conclusions about the classification of a stream’s temperature or thermal regime and which fish species may or may not occur require caution.

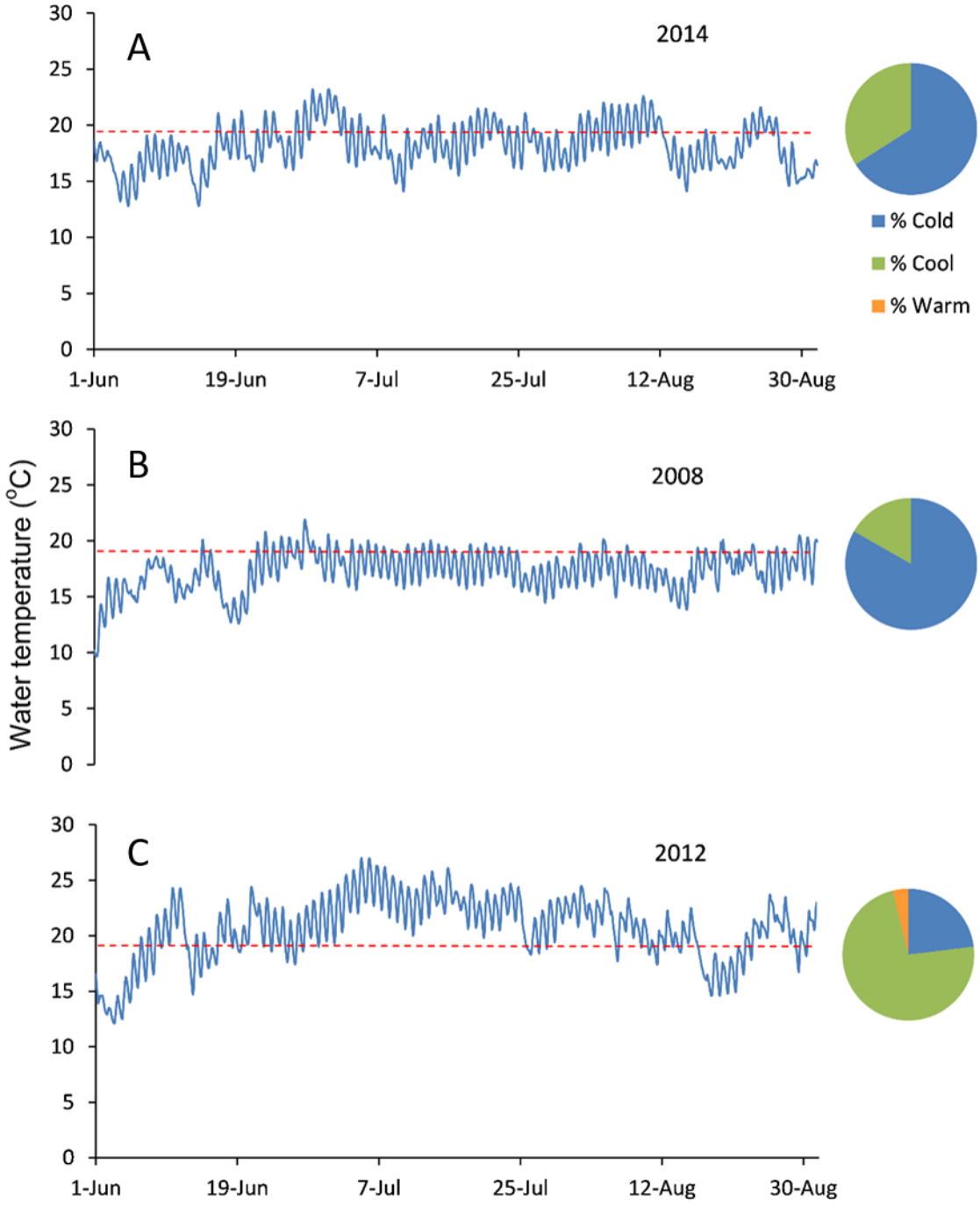


Figure 1. Annual variation in stream temperatures for Goulais River near Kirby's Corner during an average summer (A), a cold La Niña summer (B), and a hot El Niño summer (C). Points above the red lines indicate periods when the temperature of the main channel flow is likely stressful for brook trout: 31 days in scenario A, 15 days in scenario B, and 73 days in scenario C.

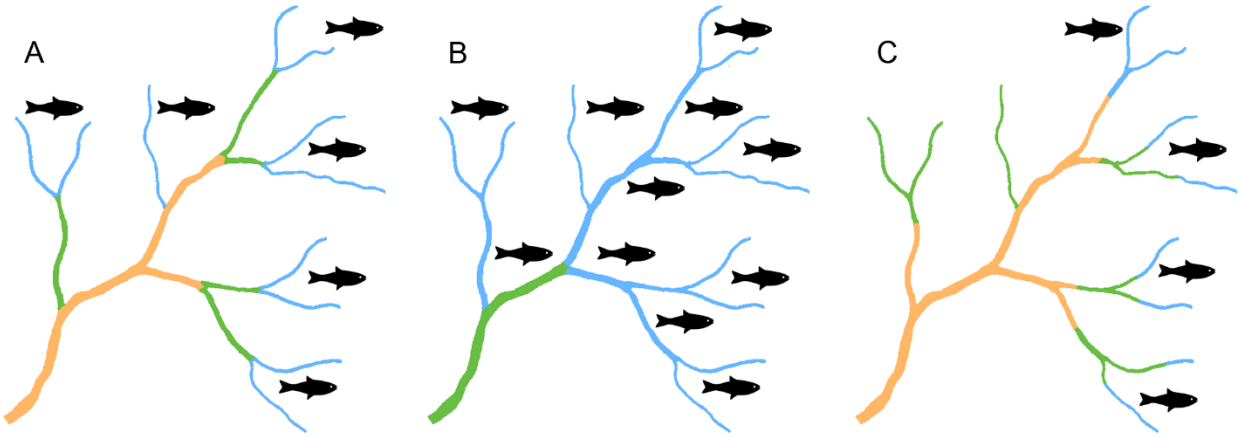


Figure 2. Annual variability in temperature across a hypothetical stream network during an average summer (A), a cold La Niña summer (B), and a hot El Niño summer (C). Blue = coldwater, green = coolwater, and orange = warmwater streams. Although temperatures are binned into classes, it is a continuous variable.

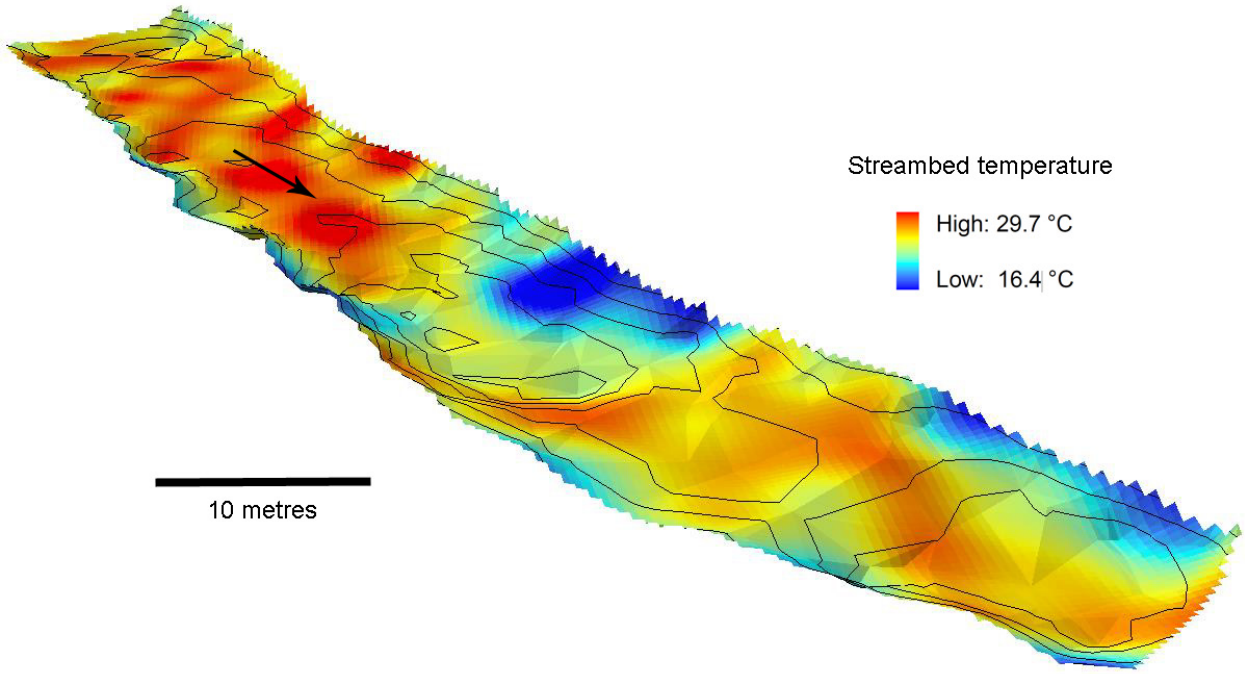


Figure 3. Small scale variation in water temperature in a stream reach near Nipigon (from R. Mackereth, Centre for Northern Forest Ecosystem Research, MNRF). Patches of cooler water are often found around tributaries and their confluence plumes, deep groundwater seeps, thermal stratification of deep pools, and hyporheic exchange.

Thermal preferences and tolerances of fish

Fish body temperatures are typically equal to or within a few fractions of a degree of the surrounding water temperature. Fish are highly dependent on water temperature to maintain their biochemical, physiological, and life history processes (Brett 1971, Caissie 2006). Metabolic rates in fishes slowly increase as the preferred temperature is approached from below and drop rapidly after it is exceeded, reaching zero at the lethal temperature (Vasseur et al. 2014). This pattern indicates a narrow range of optimal temperatures at the top of the curve (Figure 4).

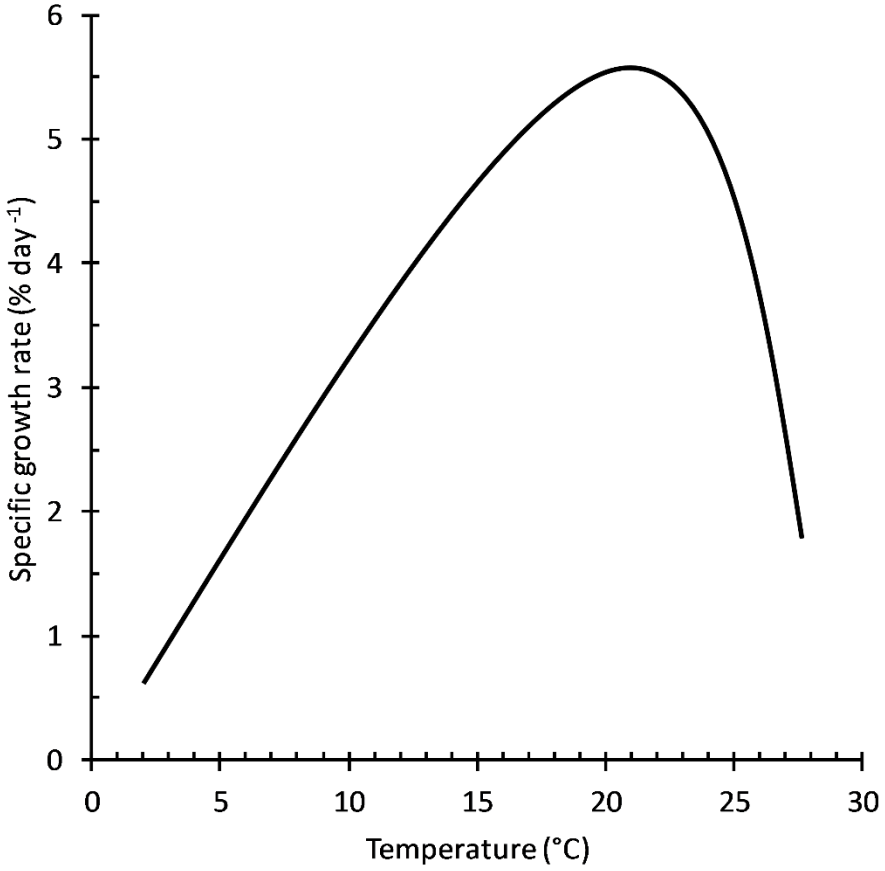


Figure 4. The general shape of the specific growth rate of freshwater fishes in relation to water temperature. The right skewed bell shape is common for many fish species.

Metabolically, fish near their thermal optimum require more food to maintain a positive growth rate; if food is plentiful they will grow very fast, if food is scarce they will lose weight and may decide to find cooler water where the metabolic demands are more amiable with forage availability. Chadwick and McCormick (2017) found that the specific growth rate of brook trout was zero when water temperature was above 23.5 °C. At temperatures greater than 23.5 °C, brook trout grew more slowly despite being fed to satiation.

Although fish have well defined temperature preferences and their distribution is related to stream temperature, they can inhabit a range of temperatures through behavioural adaptations. For example, they can inhabit streams that are several degrees warmer than their preferred temperature; how much warmer depends on how long they are there, how much food is available, and whether they can find cooler patches of water. Behavioural thermoregulation has been noted for multiple species of fish (Huntsman 1942, Gibson 1966, Berman and Quinn 1991, Tanaka 2000). For instance, Berman and Quinn (1991) found that Chinook salmon (*Oncorhynchus tshawytscha*) were able to consistently maintain internal body temperatures 2.5 °C cooler than the observed ambient river temperature. Patches of cooler water are often found around cool tributaries and their accompanying confluence plumes, deep groundwater seeps, thermal stratification of deep pools, and hyporheic exchange. Every fish has an upper temperature limit at which they perish but they can tolerate temperatures higher than their preferences (Figure 5). For example, brook trout can tolerate maximum daily mean temperatures of 21 °C for approximately 60 days. In comparison, they can only tolerate 3 days

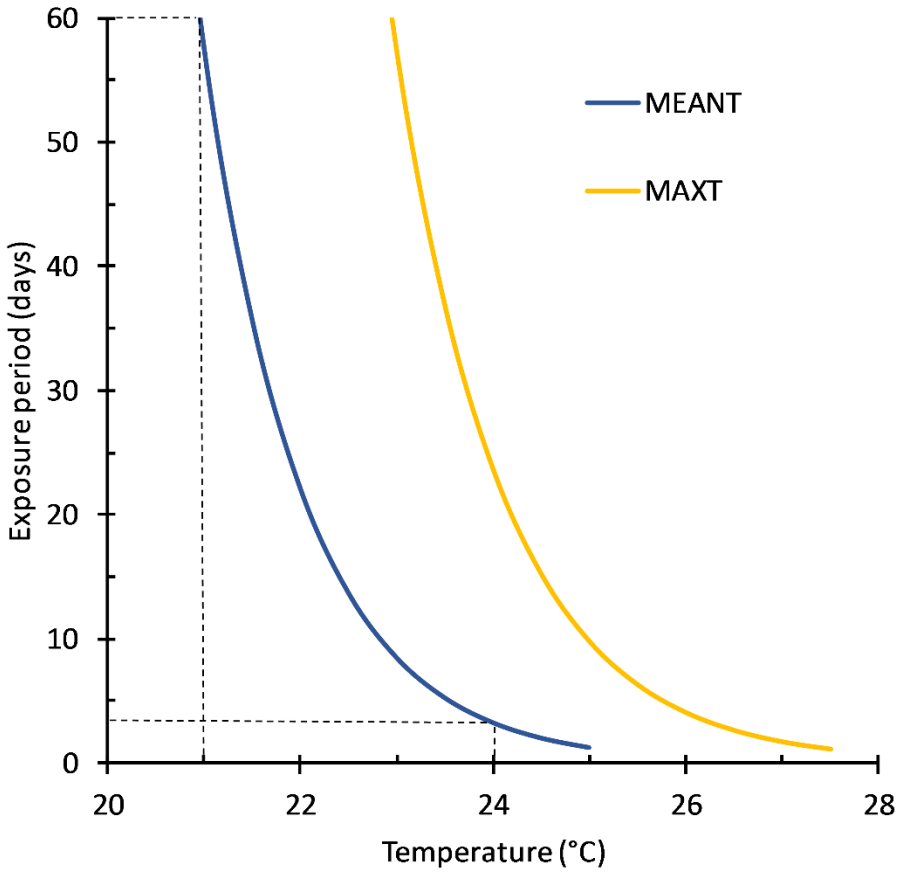


Figure 5. Estimates of 2 measures of thermal tolerance — the maximum daily mean temperature (MEANT) and the maximum daily maximum temperature (MAXT) of brook trout (adapted from Wehrly et al. 2007). Dotted lines are a guide to specific temperatures and their corresponding exposure period.

at a maximum daily mean temperature of 24 °C (Wehrly et al. 2007). Coincidentally, Chadwick et al. (2015) found that gill heat shock proteins and plasma glucose in brook trout increased at 21 °C. Because warm water holds less dissolved oxygen than cold water, at higher temperatures the oxygen content may be too low to meet fish metabolic needs.

Temperature classification

Traditionally stream temperature has been classified into cold, cool, and warm water types. More recently several authors have developed additional classes (Lyons et al. 2009) to include cold, cold transition, warm transition, and warm and a 5-class system of cold, cold–cool, cool, cool–warm, and warm (Chu et al. 2009). The threshold temperatures for classes are not standardized, varying within and among regions in North America. Often coldwater streams are defined by a threshold temperature (e.g., mean July temperature <17.5 °C) and or by the presence of coldwater species such as trout. As described above, stream temperatures vary in time and space, making their thermal classification difficult. Similarly, fishes can be found in a range of water temperatures and have physiological and behavioural coping strategies that allow them to tolerate temperatures warmer and colder then they prefer, making their classification (e.g., coldwater fish) difficult.

Given the complex nature of stream temperature, a misconception is that coldwater fishes will only be observed in coldwater streams. In fact, some coolwater streams support the highest biomass and production of trout (Lyons et al. 2009). During the summer months, warmwater fishes (e.g., catfish and bass) can often be found amongst coldwater fishes. Likewise, warmwater streams may provide habitat for cool- and coldwater species during non-summer months. Coolwater fish assemblages significantly overlap with warmwater and coldwater streams, and coolwater streams do not have diagnostic species (Lyons et al. 2009).

Some U.S. states have split the coolwater class into 2 sub classes, *cold transition* with a July mean temperature of 17.5 to 19.5 °C and *warm transition* with a July mean temperature of 19.5 to 21.0 °C (Lyons et al. 2009). The number and location of coldwater and warmwater streams does not change. This subclass structure decreases the overlap to some degree because abundances of warmwater fishes are much lower at cold-transition sites and generally absent at coldwater sites (Lyons et al. 2009). Similarly, coldwater fishes have lower abundances at warm-transition sites and are almost absent from warmwater sites during the summer.

While this definition of thermal classes has appeal, annual variation can lead to different classifications, particularly for streams with temperatures near the class thresholds. For example, a stream measured as coolwater in 1998 may be found to be coldwater when resampled in 1999 or vice-versa (Figure 6). In addition, landscape models used to predict water temperature with low density data are typically in the multiple regression family with moderate accuracy (R^2 ~ 0.65) and a root mean square error of 2 to 3 °C. This degree of error spans the cold transition thermal class (i.e., July mean temperature between 17.5 and 19.5 °C) described by Lyons et al. (2009) making it difficult to place a stream in this class with certainty. For Ontario streams, we found that the average range for average July temperature among 78 streams was 3.5 °C with a range of 6.4 °C (low of 1.2 to a high of 7.6 °C).

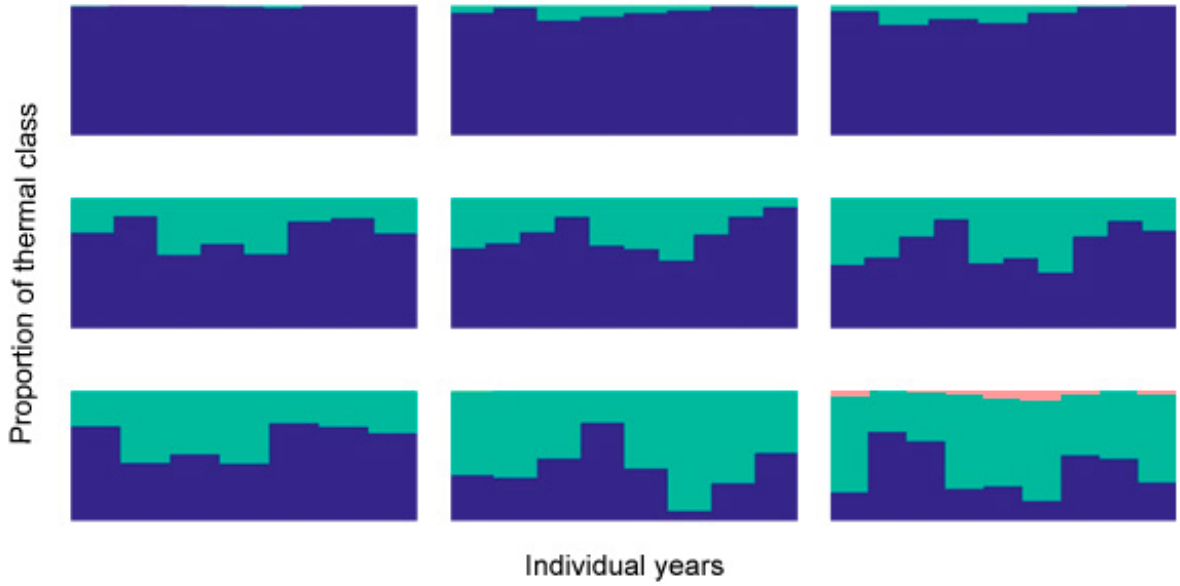
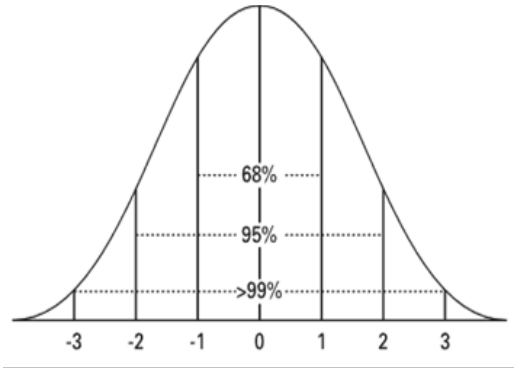


Figure 6. Annual variability of the proportion of thermal classes: coldwater (≤19 °C; blue), coolwater (19–25 °C; green), and warmwater (≥25 °C; red) for 9 Ontario streams. Note the differences in the proportions of the coldwater thermal class among streams and the variability among years.

Temperature classification with probabilities

Most predictive models produce a temperature value based on average temperature providing no indication of annual variability (Vasseur et al. 2014). Point-in-time temperature sampling using the Stoneman and Jones (1996) or Chu et al. (2009) approaches is also vulnerable to annual variation in air temperatures. Although Stoneman and Jones (1996) noted minimal variation among years, they had only 2 sites, both on Wilmot Creek, and 2 years (1991, 1994) of data to draw on; both were thermally stable coldwater sites. Streams with more surface run off (warmer water) will show greater annual variability. Certainly, a stream that is 16° C on a hot day is classified as a coldwater type but this is not necessarily true for a stream near a threshold temperature (e.g., 18.5 °C).

A more robust approach entails using multiple years of field data; however, this may require 12 or more years of data (Jones and Schmidt 2018) to create probabilities for given temperatures (e.g., with 10 years of stream temperature data only 2 years, or 20%, had temperatures above 18.5 °C). Alternatively, model predictions could be made using multiple years of air temperature data, such as 30 years of climate data with 30 average July air temperatures, as model inputs. This would provide 30 predicted stream temperatures per site/reach that could be used to make a distribution and provide probabilities for different temperature thresholds (e.g., probability of an average July water temperature greater than 18.5 °C).



$$Z = \frac{X_i - \mu}{\sigma} \qquad Z = \frac{18.5 - 17}{0.8}$$

$$Z = 1.875$$

$$P = 0.97$$

Figure 6. Illustration of the normal curve and z-score calculation based on the mean and standard deviation for stream temperature in relation to a thermal threshold of 18.5 °C, a measure of uncertainty useful in making decisions about thermal class membership. For example, based on 30 years of data and a standard deviation of 0.8 °C, a stream with an average July temperature of (i) 17 °C would have a high probability (P=0.97) of belonging to the coldwater class, (ii) 20 °C would have a high probability (p=0.94) of belonging to the coolwater class, and, in contrast, (iii) 21.5 °C would have a low probability for both the cool and warm classes (see Figure 7: three classes).

Stream temperature can be classified in several ways varying from 3 to 4 classes (Figure 7). We chose threshold temperatures similar to those used by Lyons et al. (2009), i.e., coldwater <17.5 °C, cold transition 17.5–19.5 °C, warm transition 19.5–21.0 °C, and warm >21.0 °C. We increased the lower threshold temperature by 1.0 °C because <17.5 °C was too low based on knowledge of Ontario streams and relationships between brook trout occupancy and stream temperature. We developed a 5-class approach that combines thermal class and probability (Figure 7). Our 5-class approach is consistent with those documented by Chu et al. (2009) but the classes were determined using different methods. The Chu et al. (2009) nomogram uses a daily maximum air temperature taken during the summer, whereas, our aquatic ecosystem classification (version 2) uses multiple estimates of average July air temperature.

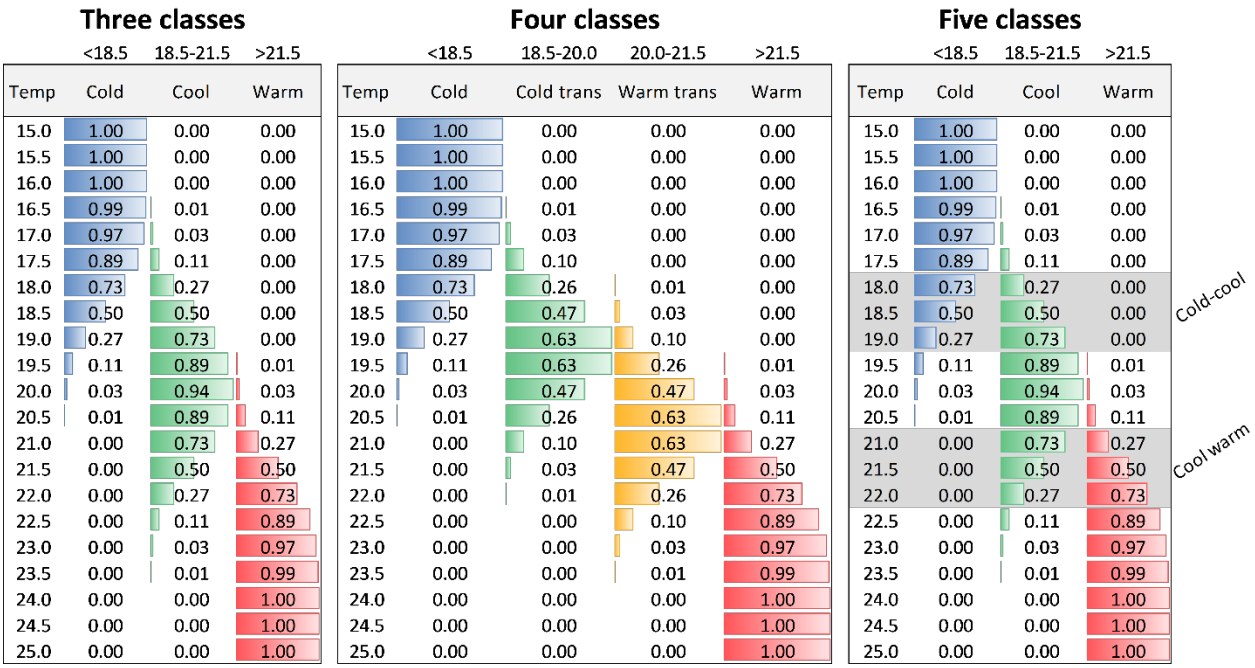


Figure 7. Probabilities of stream thermal classification using 3 approaches and a standard deviation of 0.8 °C, with colours indicating classes and probabilities. The 3 and 4 class approaches differ in the threshold values. In the 5-class framework, thermal class is determined by the highest probability over a threshold, in this case, p>0.8. For example, a stream is considered cold if its average July temperature is 17 °C because the highest probability is 0.97. A stream would be considered cold-cool if its average July temperature is 18.5 °C because it has a 0.5 probability of being cold or cool, i.e., it is transitional. The grey bands illustrate transitional temperatures cold-cool and cool-warm where the probability of membership to cold, cool, or warm is low (e.g., <0.8). The 5-class method explicitly incorporates uncertainty because class is determined by the probability.

Brook trout

Stream temperature is just one of several determinants of brook trout presence or abundance and the provincial aquatic ecosystem classification (Jones and Schmidt 2017) does not directly predict brook trout occupancy. For the purposes of protecting brook trout, it is more accurate to directly predict their occurrence on the landscape with a probabilistic model. Accurate models require good input data and field techniques (e.g., high effort electrofishing) that have a high likelihood of detecting brook trout presence. During the hot summer months, brook trout often group together near thermal refugia resulting in poor detection probabilities (e.g., many zeros and a few large catches). The summer months are also when their distribution is most restricted. Habitats used for spawning and overwintering during other times of the year are likely in other parts of a stream network. Also, their summer distribution will differ in a cool-wet summer from that in a hot-dry summer (Figure 2). Even if brook trout are not found, perhaps because of a barrier, the water might be cold and support trout downstream. A stream does not need to host brook trout to be considered brook trout habitat. Ultimately, weight of

evidence and precautionary approaches are needed to effectively predict what is habitat. Weight of evidence refers to available information about a stream of interest, which could be anecdotal, traditional ecological knowledge, or probabilistic models. Precautionary decisions generally err on the side of caution and provide protections where harm is possible and extensive scientific knowledge on the matter is lacking or suggests a plausible risk. Precautionary measures are relaxed if information emerges that provides evidence that harm is unlikely.

Models that can be used to predict stream temperature and where fish are found on the landscape are needed to support fisheries policy and management decisions. We have developed a predictive model for brook trout in southern Ontario (Figure 8). This information can be used to strategically prioritize field activities (e.g., electrofishing, eDNA) to focus on streams with higher probabilities of occurrence. In the absence of such maps, field crews do not know where to sample and how best to make efficient use of their limited time. For instance, biologists who need to identify coldwater streams along a proposed pipeline route or direct consultants to sample certain streams.

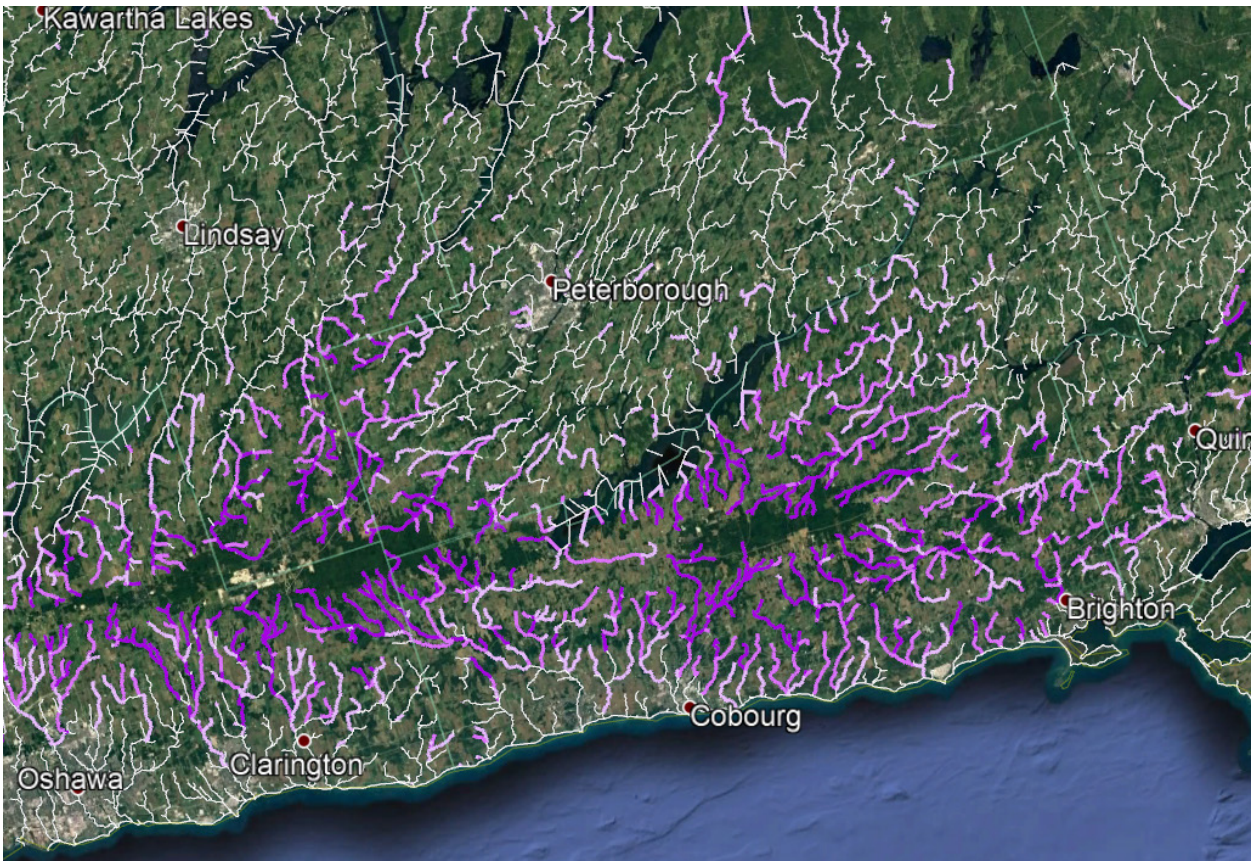


Figure 8. Predicted probability of brook trout presence during the summer for the north shore of Lake Ontario. The darker the stream colour, the higher the probability of brook trout presence.

Next steps

Maps similar to those developed for brook trout are needed for Ontario's north (i.e., Boreal Shield and Hudson Bay Lowlands). Given the data requirements for the extensive area of northern Ontario and that launching a field campaign over such a large area would require a great deal of time and resources, we propose to 'crowd-source' presence/absence information to use for modelling.

We will continue to build on stream classification work to develop tools that can be used to better understand stream temperatures and to fine tune thermal classifications to support fisheries management in Ontario.

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