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Water Temperature Analysis of the North Branch Au Sable River, Michigan, and Implications to Salmonid Populations

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Abstract

Ambient stream water temperatures affect salmonid movement and survival with fish actively seeking thermal refugia from warming waters. This study sought to investigate the potential role of water temperature in the perceived decline in native Brook Trout *Salvelinus fontinalis* and non-native Brown Trout *Salmo trutta* populations in the North Branch Au Sable River by fishers and reported to resource managers in 2018 and 2019. Water temperature was analyzed at nine stations within the North Branch Au Sable River in 2021 and 2022. A total of 61,390 temperature observations were collected with 58.0% exceeding the optimal growth threshold for Brook Trout of 16°C; 37.9% exceeding the movement threshold for Brook Trout of 18°C; 3.4% exceeding the upper limit for positive growth for Brook Trout of 23.4°C; and 28.6% exceeding the optimal growth threshold for Brown Trout of 19°C. The maximum daily water temperatures recorded for each year were 27.58°C in 2021 and 26.89°C in 2022. The availability of cold water thermal refugia is critical to the viability of native Brook Trout populations in the North Branch Au Sable River and its tributaries. Efforts should be taken to increase ambient stream water temperature monitoring year-round and to determine the size, frequency, and availability of thermal refugia within the watershed to increase the likelihood of a system resilient to the impacts of a warming climate.

Introduction

Perceived declines in native Brook Trout *Salvelinus fontinalis* and non-native Brown Trout *Salmo trutta* populations in the North Branch Au Sable River (NBAS) were brought to the attention of resource managers in 2018 and 2019. Proposed causes for the population decline were predators, discharge of chemicals, disease, organic contaminants and/or pesticides, winter severity, long-term population decline, lack of food, and changes in streamflow (Godby 2020). These hypothesized causes were examined and all except temperature regime, streamflow, and long-term population declines were ruled out (Godby 2020). While the NBAS was held in high regard for its healthy Brook Trout population, trend data have shown declining populations of both Brook and Brown trout since approximately 1985 (Figure 1) with potential lack of recruitment (Godby 2020).

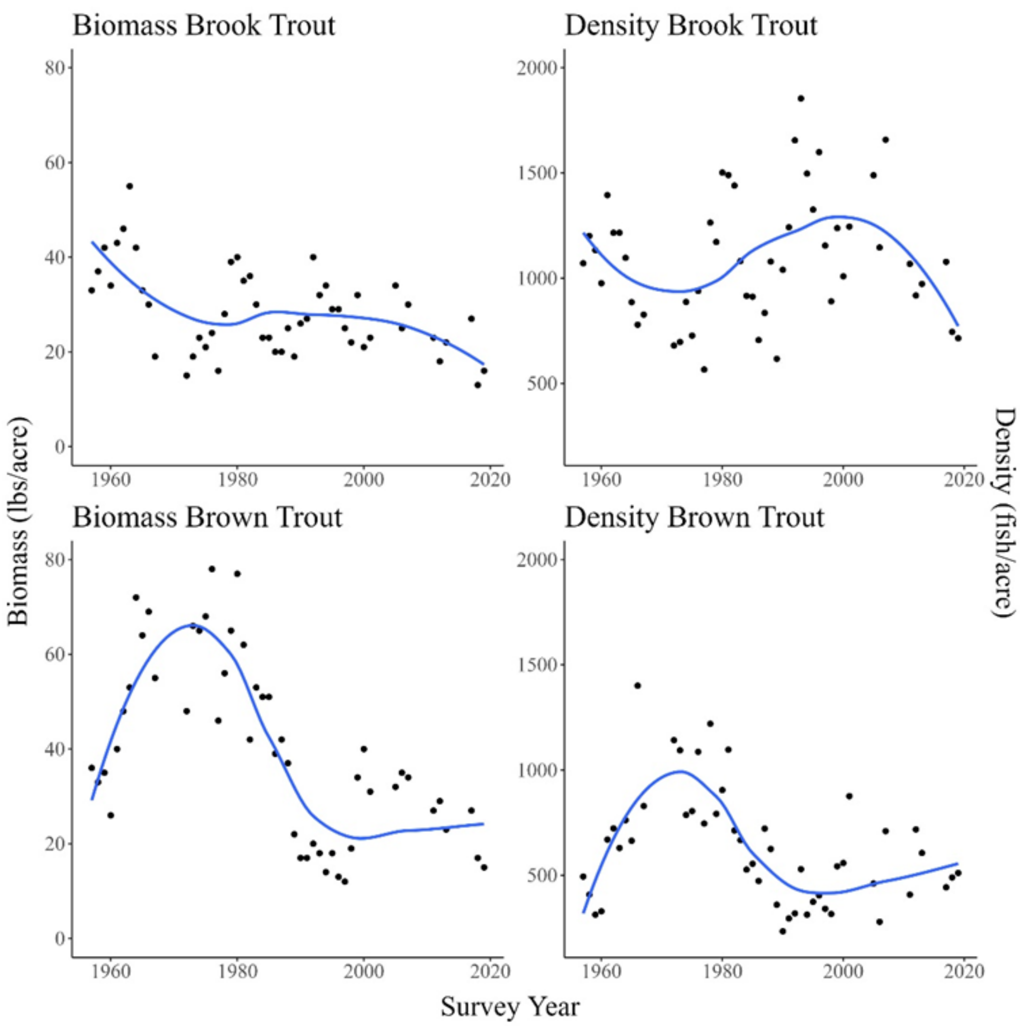


FIGURE 1. Biomass and density of Brook Trout (upper panels) and Brown Trout (bottom panels) from 1957–2019 on the North Branch Au Sable River. The blue line is a LOESS regression, used to show a smoothed trend in abundance and biomass. Data obtained by the Stream Population Trend Viewer (MI DNR 2021).

Climate change may affect salmonid populations in critical ways including alterations in precipitation and ambient temperatures (Carlson et al. 2017). This may translate to water temperatures exceeding the thermal optimal growth range for Brook Trout (11.0–16.0°C; Goble et al. 2018) and Brown Trout (12.0–19.0°C; Goble et al. 2018). The duration of time and frequency at which temperature exceeds these limits throughout the year may provide a better appreciation of the risks for this Brook Trout population. Further, the frequency at which temperatures near or exceed 23.4°C, which has been described as the upper limit for positive growth (ULPG) in Brook Trout (Chadwick 2014), was considered in this study. The lethal temperature limit for Brown Trout (26.7°C; Solomon and Lightfoot 2008), while higher than that of Brook Trout (25.3°C; Raleigh 1982), was also considered as an additional threshold.

Changes in flow during critical periods may also adversely impact salmonid populations. Increased discharge in autumn and winter has potential to dislodge eggs of fall spawning salmonids. Alevin and fry are particularly vulnerable to increases in spring flows such that increased discharge has the potential to produce weak year classes. Periods of decreased discharge may also negatively affect fish populations through factors such as decreased habitat availability or ice thickness. These negative relationships between high and low flows and fish populations have been well documented in previous research (Cattanéo et al. 2002; Zorn and Nuhfer 2007a, 2007b; Bradford and Heinonen 2008; Grossman et al. 2012; Nuhfer et al. 2015). Godby (2020) suggested year-round temperatures and discharge warranted additional examination, leading to the need of this study. Changes to this historically stable groundwater fed system could adversely affect salmonid populations. While this study did not focus on flow rates, future research comparing historic and contemporary flow regimes is warranted.

This study aimed to address spatial and seasonal temperature patterns in the NBAS in the northern Lower Peninsula of Michigan (Figure 2) to determine if water temperature exceeded critical thresholds: the thermal optimal growth range and lethal limits for Brook (11.0–16.0°C, 25.3°C) and Brown (12.0–19.0°C, 26.7°C) trout; the ULPG (23.4°C) for Brook Trout, and the movement threshold (18.0°C) for Brook Trout, and if so, quantify the frequency and duration of such exceedance. These data can act as a starting point for long-term monitoring of environmental and ecosystem conditions such as stream temperatures and to explain the potential shift in salmonid populations within the NBAS.

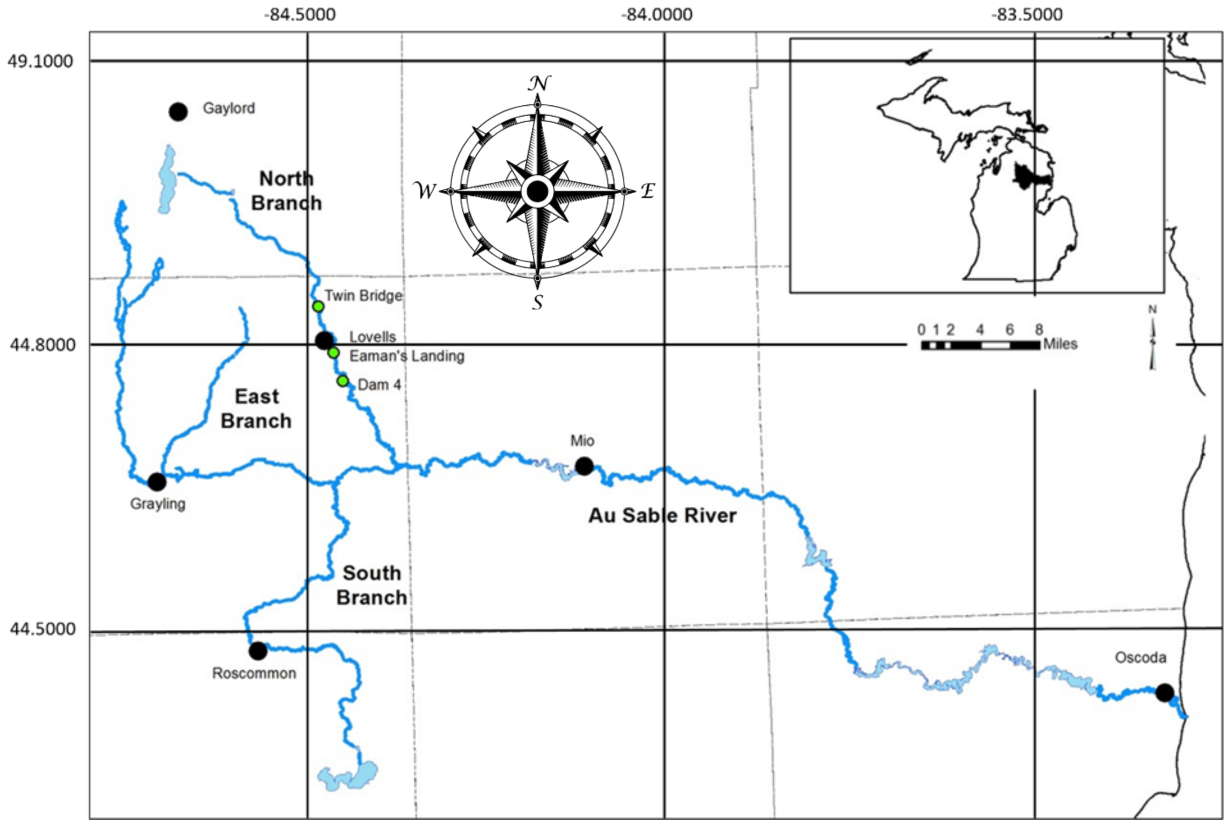


FIGURE 2. The Au Sable River and its primary tributaries, the North Branch, East Branch, and South Branch, located in the northern Lower Peninsula of Michigan, USA. Dashed grey lines are Michigan county borders. Black circles indicate major cities/towns; green circles represent historic trout population estimate sites that were sampled annually on the NBAS. Lighter blue represents lentic waters while brighter blue represents lotic.

Methods

Passive HOBO® pendant MX water temperature data loggers were placed by Michigan Department of Natural Resources (MI DNR) technical staff at nine stations (Figure 3) within the NBAS during July 2021. The loggers were retrieved October 2021 for data downloading and winter storage, redeployed in the same locations in April 2022 and removed at the end of September 2022. The Twin Bridge station represents a long-term MI DNR temperature logging location and includes an extended date range of data collection as compared to the other stations. Each logger was set to record the temperature once per hour, on the hour.

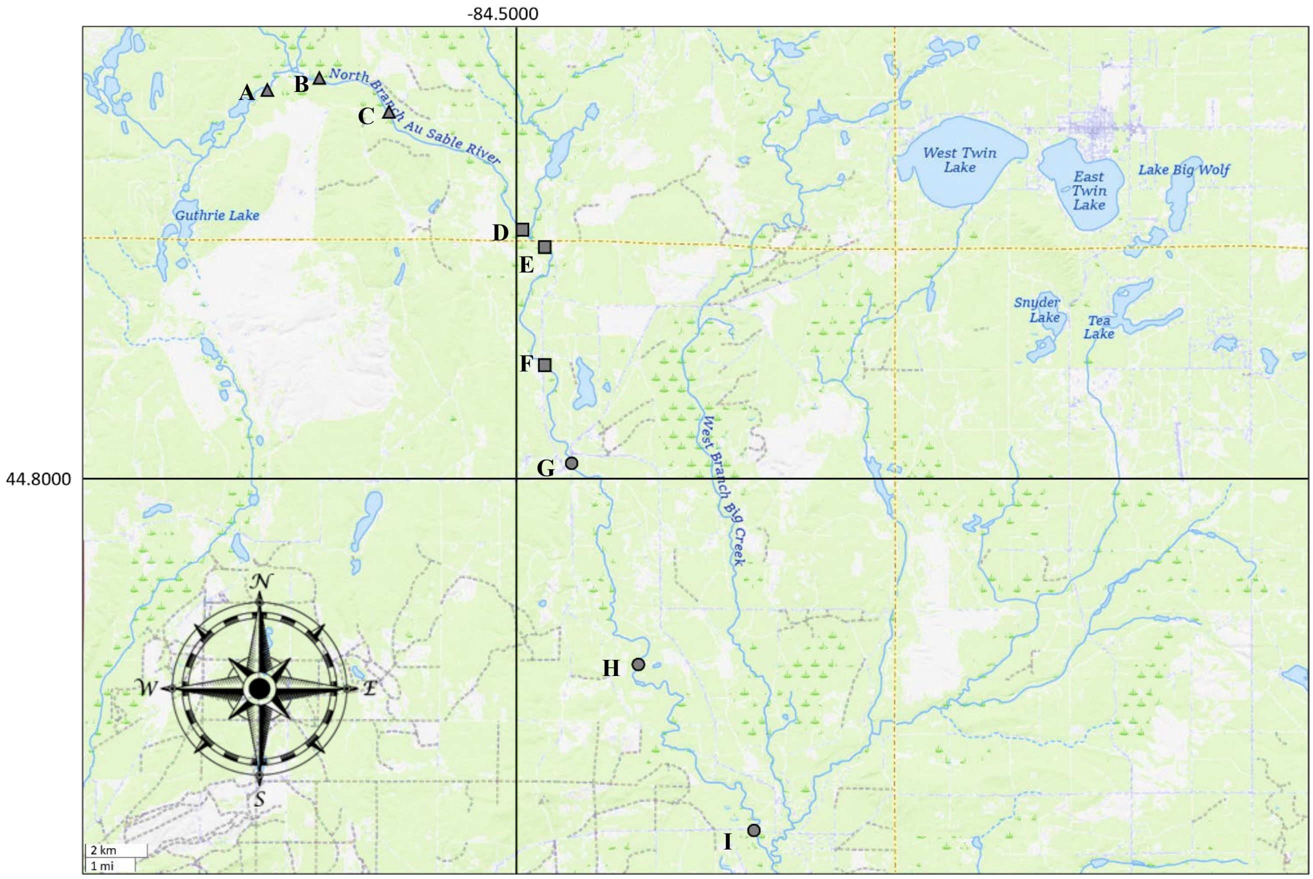


FIGURE 3. Temperature logger placement on the North Branch Au Sable River, Michigan, USA. The logger array was separated into three sections: upstream (grey triangles), mid-stream (grey squares), and downstream (grey circles). From upstream-most to downstream-most, the station names and their associated abbreviations were: Below Chub Lake (A), Turtle Creek (B), The Ford (C), Above Crapo Creek (D), Below Crapo Creek (E), Twin Bridge (F), Lovells (G), Dam 4 (H), and Kelloggs (I).
Note: map generated using https://streamstats.usgs.gov/ss

Temperature data were analyzed in RStudio using the tidyverse, ggbreak, readr, and doBy packages after being downloaded from the HOBO® mini loggers by MI DNR staff (Xu et al. 2021). Daily mean, minimum, and maximum temperatures were calculated for each day at each station. Optimal growth temperatures for Brook Trout and Brown Trout were assumed to be the upper end of the thermal optimal range reported by Goble et al. (2018). The degree of temperature stress was determined for each species using the optimal growth temperatures as the baseline. Degree of stress was calculated using the following formula:

$$S_d = \overline{T_d} - O_x$$

where S_d is the degree of temperature stress for the species of interest on the day sampled, $\overline{T_d}$ represents the mean daily water temperature, and O_x the optimal growth temperature for either Brook (16.0°C) or Brown trout (19.0°C). Daily temperature data were further analyzed to examine frequency and proportion of exceedance of the critical thresholds: the optimal growth temperature and lethal limits for Brook (16.0°C, 25.3°C) and Brown (19.0°C, 26.7°C) trout; the ULPG (23.4°C) for Brook Trout, and the movement threshold (18.0°C) for Brook Trout.

Results

Total sample days ranged from 112–164 in 2021 and 167 in 2022. The difference in sample days in 2021 was attributed to Twin Bridge (n = 164) being a long-term sampling location for MI DNR which had slightly different logger deployment and collection than the other stations in 2021 (Tables 1, 2), however all data for Twin Bridge were included in this dataset. A total of 61,390 hourly temperature data points were collected. Of those data points, 58.0% were greater than or equal to the optimal growth threshold for Brook Trout of 16.0°C; 28.6% were greater than or equal to the optimal growth threshold for Brown Trout of 19.0°C; and 3.4% were greater than or equal to the ULPG for Brook Trout of 23.4°C (Table 3). A total of 37.9% were greater than 18.0°C, the threshold which Petty et al. (2012) found to induce increased movement (Table 3). The maximum daily temperature recorded for each year of sampling were 27.6°C at station A, Below Chub Lake (21-Aug-2021), 26.9°C at station D, Above Crapo Creek (15-Jun-2022, 23-Jul-2022), and station F, Twin Bridge (15-Jun-2022).

The mean daily temperatures recorded by station exceeded the optimal temperature for Brook Trout 40–74% of days sampled in 2021 (Table 1; Figure 4) and 57–77% in 2022 (Table 2; Figure 4). The mean daily temperature exceeded the optimal temperature for Brown Trout 14–49% of the days sampled in 2021 (Table 1; Figure 4) and 12–61% in 2022 (Table 2; Figure 4). The highest proportion of days in excess of optimal temperature occurred at the Below Chub Lake station in both years for both species and at the Turtle Creek station for Brook Trout (16.0°C) in 2022 (Tables 1, 2). Mean daily temperatures did not exceed the lethal thermal maxima for either species during the timeframes surveyed.

TABLE 1. Summarization of 2021 temperature log data by station with total days sampled and number (n) and proportion (p) of days in which the mean and minimum daily temperature was over 16°C and 19°C. Stations are arranged from upstream-most to downstream-most.

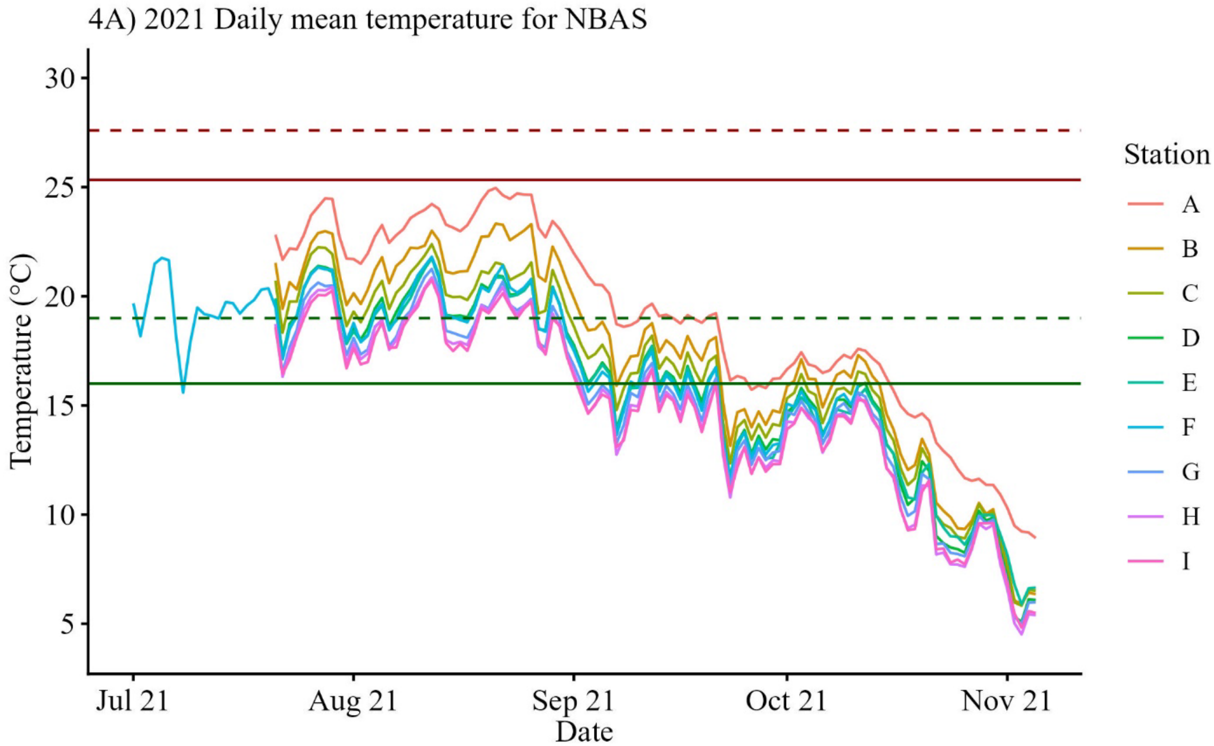
			Days Mean Above				Days Min Above			
			16°C	16°C	19°C	19°C	16°C	16°C	19°C	19°C
Station Name	Abbreviation	Sample Days	n	p	n	p	n	p	n	p
Below Chub Lake	A	113	84	0.74	55	0.49	75	0.66	47	0.42
Turtle Creek	B	112	72	0.64	44	0.39	52	0.46	24	0.21
The Ford	C	112	63	0.56	39	0.35	42	0.38	9	0.08
Above Crapo	D	118	59	0.50	32	0.27	31	0.26	3	0.03
Below Crapo	E	112	54	0.48	29	0.26	33	0.29	3	0.03
Twin Bridge	F	164	109	0.66	58	0.35	58	0.35	4	0.02
Lovells	G	112	47	0.42	19	0.17	26	0.23	2	0.02
Dam 4	H	112	46	0.41	19	0.17	24	0.21	0	0.00
Kelloggs	I	112	45	0.40	16	0.14	25	0.22	0	0.00

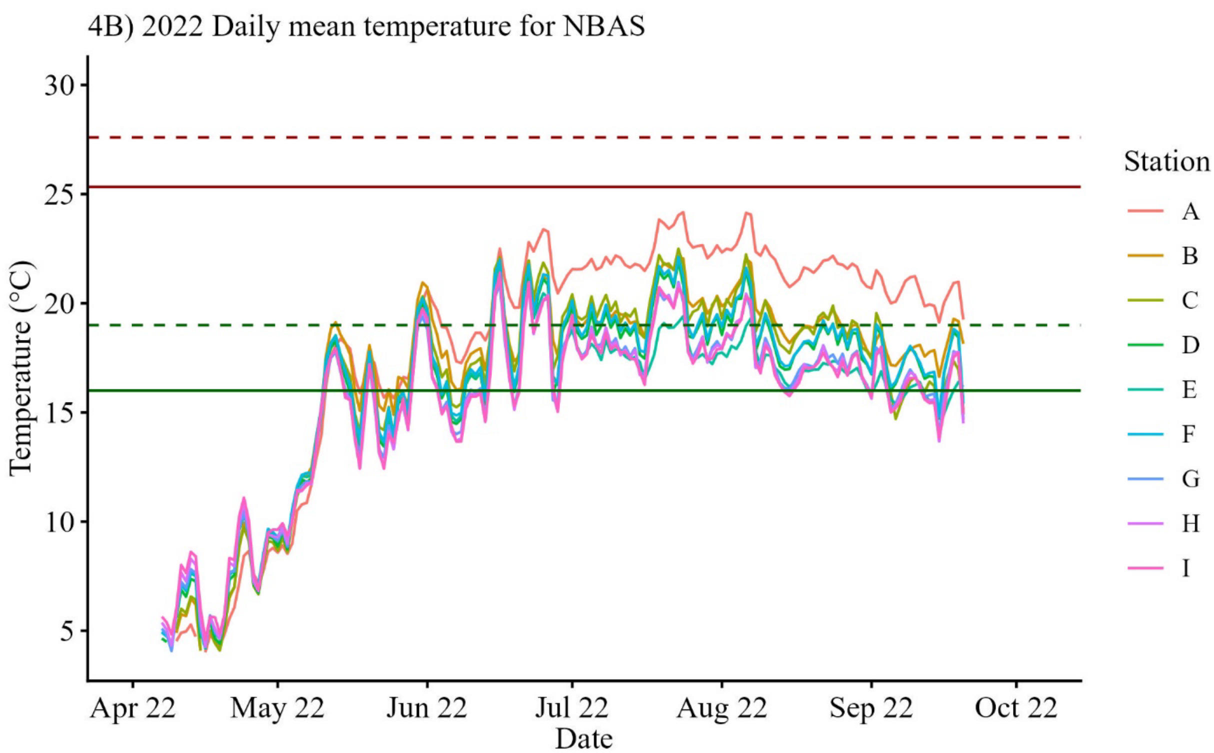
TABLE 2. Summarization of 2022 temperature log data by station with total days sampled and number (n) and proportion (p) of days in which the mean and minimum daily temperature was over 16°C and 19°C. Stations are arranged from upstream-most to downstream-most.

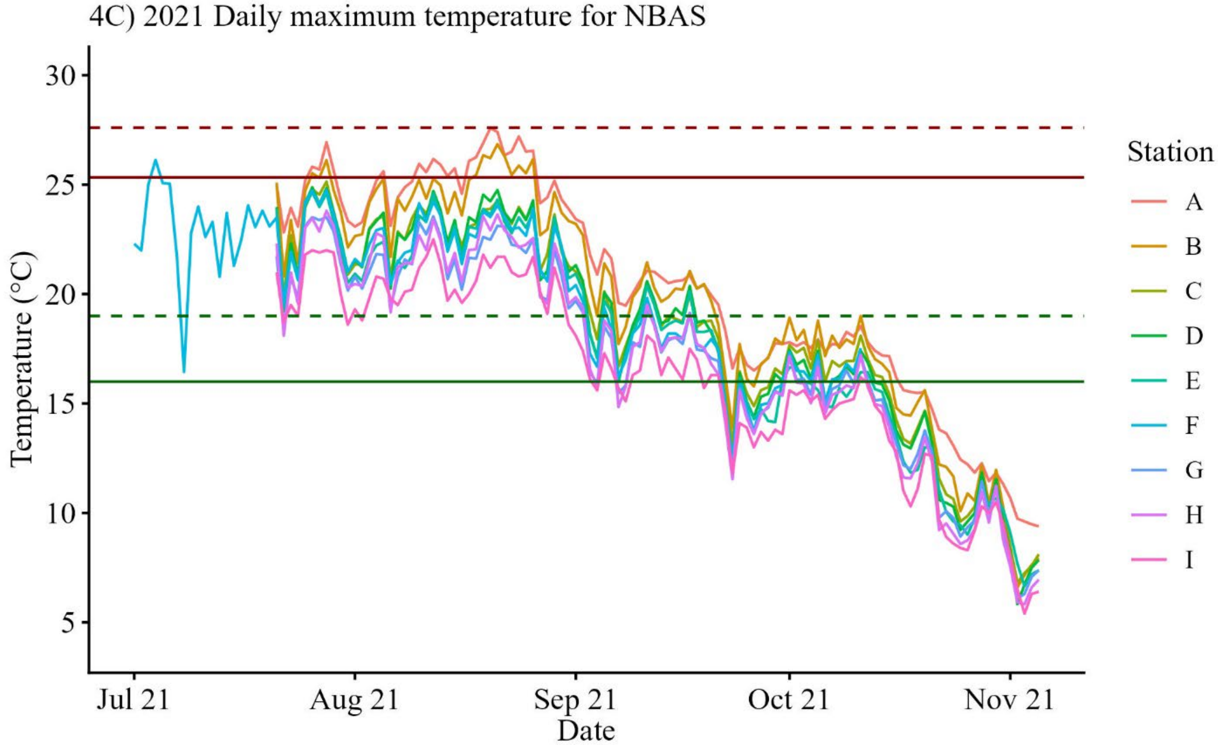
			Days Mean Above				Days Min Above			
			16°C	16°C	19°C	19°C	16°C	16°C	19°C	19°C
Station	Abbreviation	Sample Days	n	p	n	p	n	p	n	p
Below Chub Lake	A	167	129	0.77	102	0.61	123	0.74	90	0.54
Turtle Creek	B	167	128	0.77	63	0.38	103	0.62	15	0.09
The Ford	C	167	115	0.69	60	0.36	61	0.37	6	0.04
Above Crapo	D	167	112	0.67	36	0.22	34	0.20	1	0.01
Below Crapo	E	167	107	0.64	15	0.09	65	0.39	0	0.00
Twin Bridge	F	167	116	0.69	44	0.26	44	0.26	3	0.02
Lovells	G	167	100	0.60	20	0.12	23	0.14	0	0.00
Dam 4	H	167	95	0.57	22	0.13	24	0.14	0	0.00
Kelloggs	I	167	95	0.57	21	0.13	28	0.17	3	0.02

TABLE 3. Total number of temperature data points and proportion of the total data (N = 61,390) greater than or equal to the four thresholds of interest: Brook Trout optimal growth limit (≥ 16°C), Brook Trout movement threshold (> 18°C), Brown Trout optimal growth limit (≥ 19°C), and the Brook Trout upper limit for positive growth (≥ 23.4°C).

	≥ 16°C	> 18°C	≥ 19°C	≥ 23.4°C
Data points (n)	35,593	23,267	17,577	2,070
Proportion (p)	0.5798	0.3790	0.2863	0.0337


4A) 2021 Daily mean temperature for NBAS
Temperature (°C)
30
25
20
15
10
5
Jul 21
Aug 21
Sep 21
Oct 21
Nov 21
Date
Station
A
B
C
D
E
F
G
H
I


4B) 2022 Daily mean temperature for NBAS
Temperature (°C)
30
25
20
15
10
5
Apr 22
May 22
Jun 22
Jul 22
Aug 22
Sep 22
Oct 22
Date
Station
A
B
C
D
E
F
G
H
I



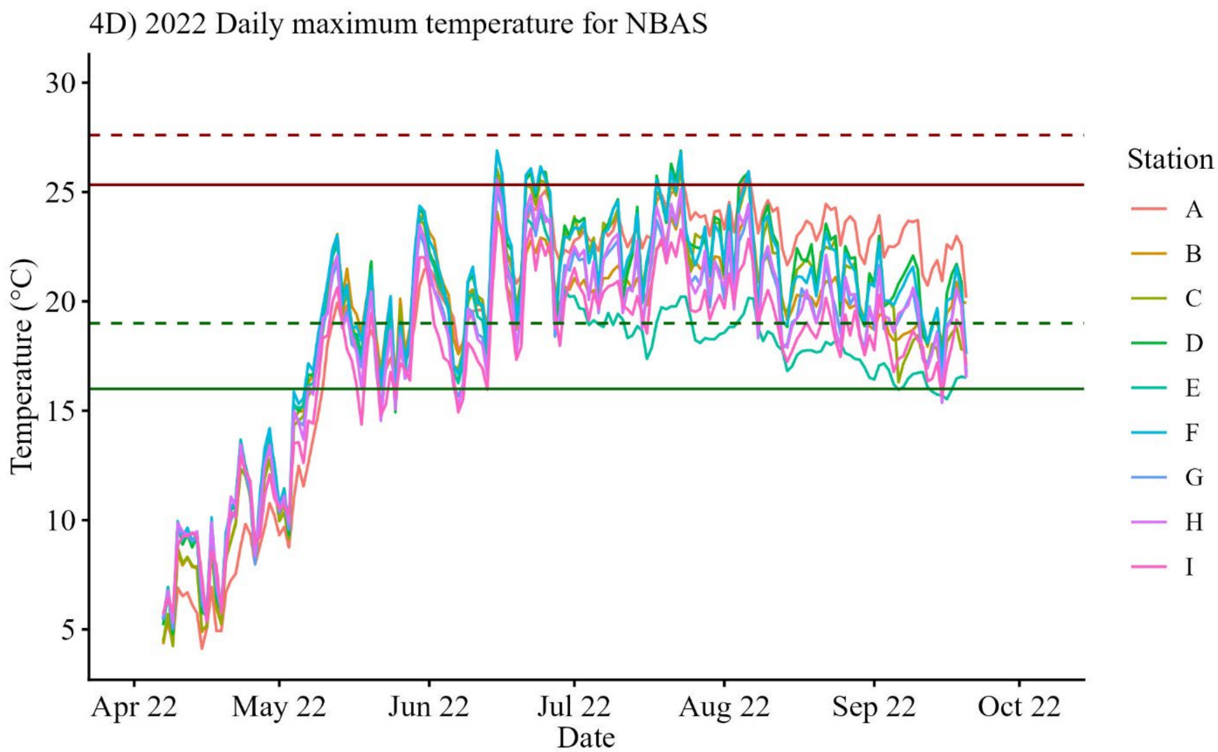
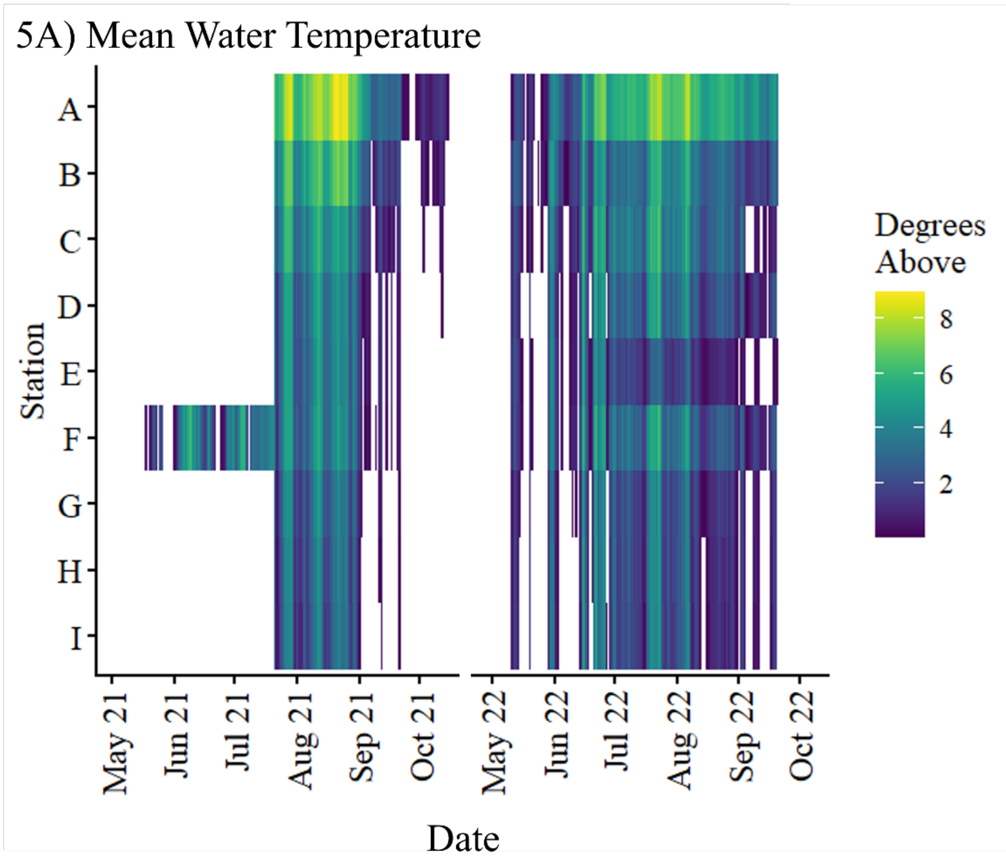
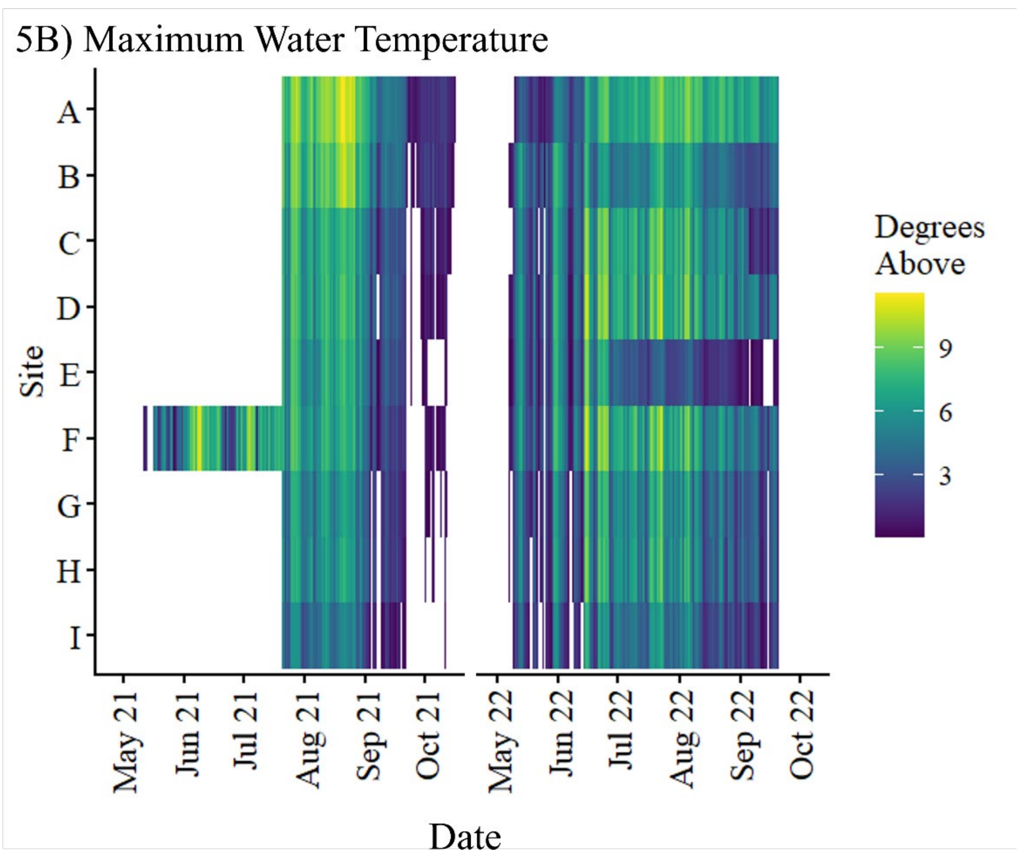


FIGURE 4. Mean daily temperature (4A and 4B) and maximum daily temperature (4C and 4D) for the North Branch Au Sable River by station from 2021–2022. Stations are shown from upstream (A) to downstream (I). Solid horizontal lines represent Brook Trout, dashed horizontal lines for Brown Trout. Horizontal green lines are representative of the optimal growth temperature (Brook Trout = 16.0 °C, Brown Trout = 19.0 °C) with red lines indicative of lethal temperature (Brook Trout = 25.3 °C, Brown Trout = 27.6 °C).

The minimum daily temperatures recorded by station exceeded the optimal temperature for Brook Trout 21–66% of days sampled in 2021 (Table 1), and 14–74% in 2022 (Table 2). The minimum daily temperature exceeded the optimal temperature for Brown Trout 0–42% of the days sampled in 2021 (Table 1) and 0–54% in 2022 (Table 2). The highest proportion of days in excess of either optimal temperature occurred at the Below Chub Lake station in both years and for both species (Tables 1 & 2). The maximum daily temperature recorded by station exceeded the lethal thermal maxima for Brook Trout at three stations in 2021: Below Chub Lake, Turtle Creek, and Twin Bridge; and at six stations in 2022: Below Chub Lake, The Ford, Above Crapo, Below Crapo, Twin Bridge, and Dam 4 (Figure 4). The temperature reached the lethal thermal maxima for Brown Trout at two stations in 2021: Below Chub Lake and Twin Bridge (Figure 4).

Overall temperature stress was highest at the Below Chub Lake station, reaching 9°C above thermal optima in 2021 and 8°C above in 2022 for Brook Trout, and 5°C above for Brown Trout in 2021 and 2022 (Figure 5). The downstream stations exhibited the least amount of overall thermal stress for both species. The Below Chub Lake station was the only station in which the daily mean temperature exceeded the ULPG for Brook Trout (Figure 6). This occurred 27 times over the course of the days observed, during July and August in both years, with the longest consecutive stretch of days in excess of 23.4°C lasting nine days, from 18–26 Aug 2021 (Figure 7). The highest degree of difference between the mean daily temperature and the ULPG was 1.6°C, occurring the day after the highest maximum temperature (27.6°C) was reached (Figure 7). On the last day of the nine-day limnological heat wave, the minimum temperature also exceeded the ULPG (Figure 7). A second limnological heat wave occurred from 19–24 Jul 2022, where the last day of the heat wave had the highest minimum temperature observed of 23.6°C, also in excess of the ULPG for Brook Trout (Figure 7).


5A) Mean Water Temperature
Station
A
B
C
D
E
F
G
H
I
Date
May 21
Jun 21
Jul 21
Aug 21
Sep 21
Oct 21
May 22
Jun 22
Jul 22
Aug 22
Sep 22
Oct 22
Degrees Above
8
6
4
2


5B) Maximum Water Temperature
Site
A
B
C
D
E
F
G
H
I
Date
May 21
Jun 21
Jul 21
Aug 21
Sep 21
Oct 21
May 22
Jun 22
Jul 22
Aug 22
Sep 22
Oct 22
Degrees Above
9
6
3

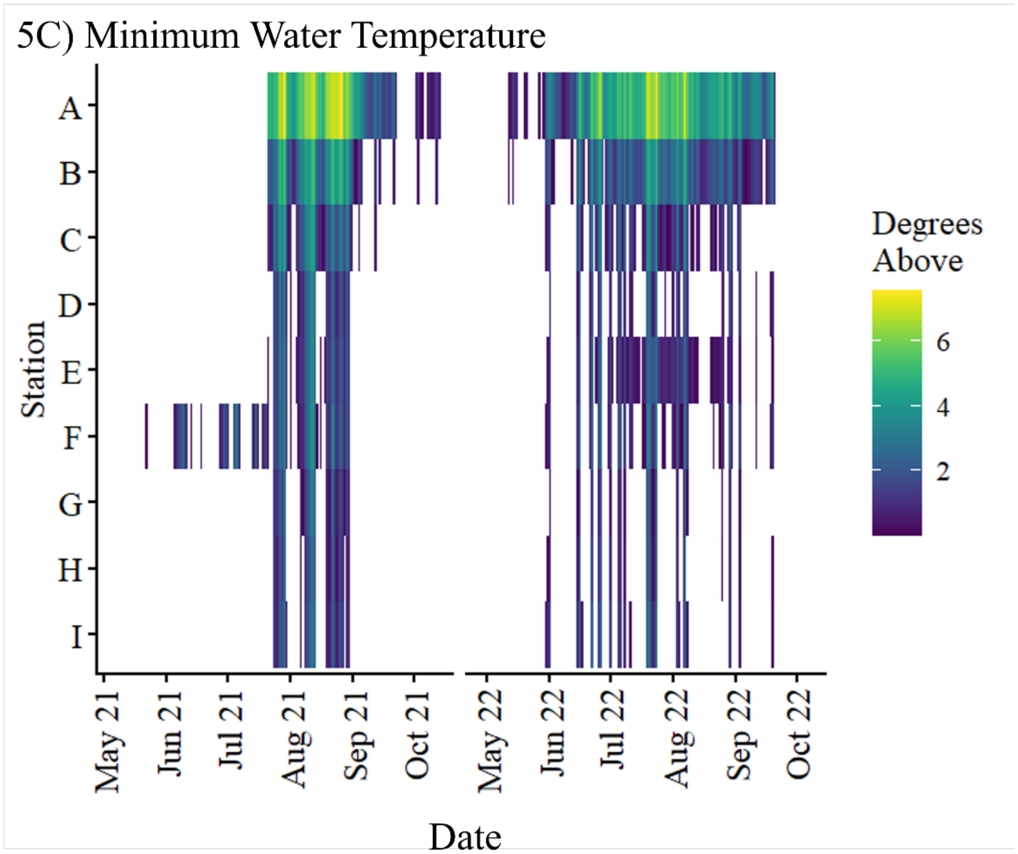


FIGURE 5. Temperature stress for the mean observed daily water temperature (panel 5A), maximum (panel 5B), and minimum (panel 5C) for Brook Trout in 2021–2022 with heat map colors representing the degree of temperature stress, i.e. the number of degrees the daily temperature was above the optimal growth temperature for Brook Trout (16 °C). For example, if the mean daily temperature was 17 °C, the degree of stress would be 1 (17 °C–16 °C = 1). Stations are ordered from upstream-most (A, top) to downstream-most (I, bottom). Note: the heatmap color scale gradient is unique to each panel.

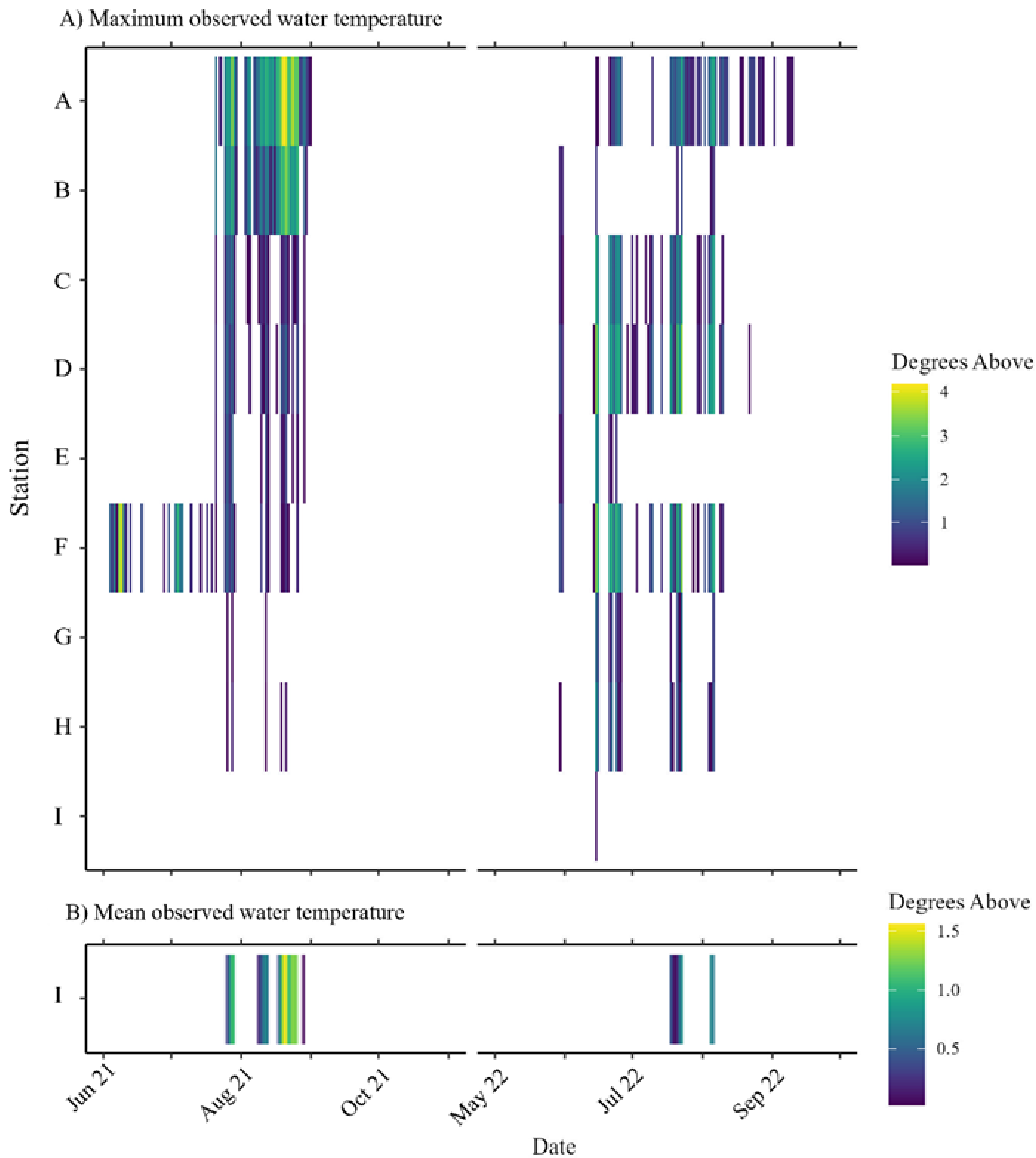


FIGURE 6. Temperature stress for the maximum observed daily water temperature (panel A) and mean (panel B) for Brook Trout in 2021–2022 with heat map colors representing the degree of temperature stress, i.e. the number of degrees the daily temperature exceeded the upper limit for positive growth (ULPG) for Brook Trout (23.4 °C).

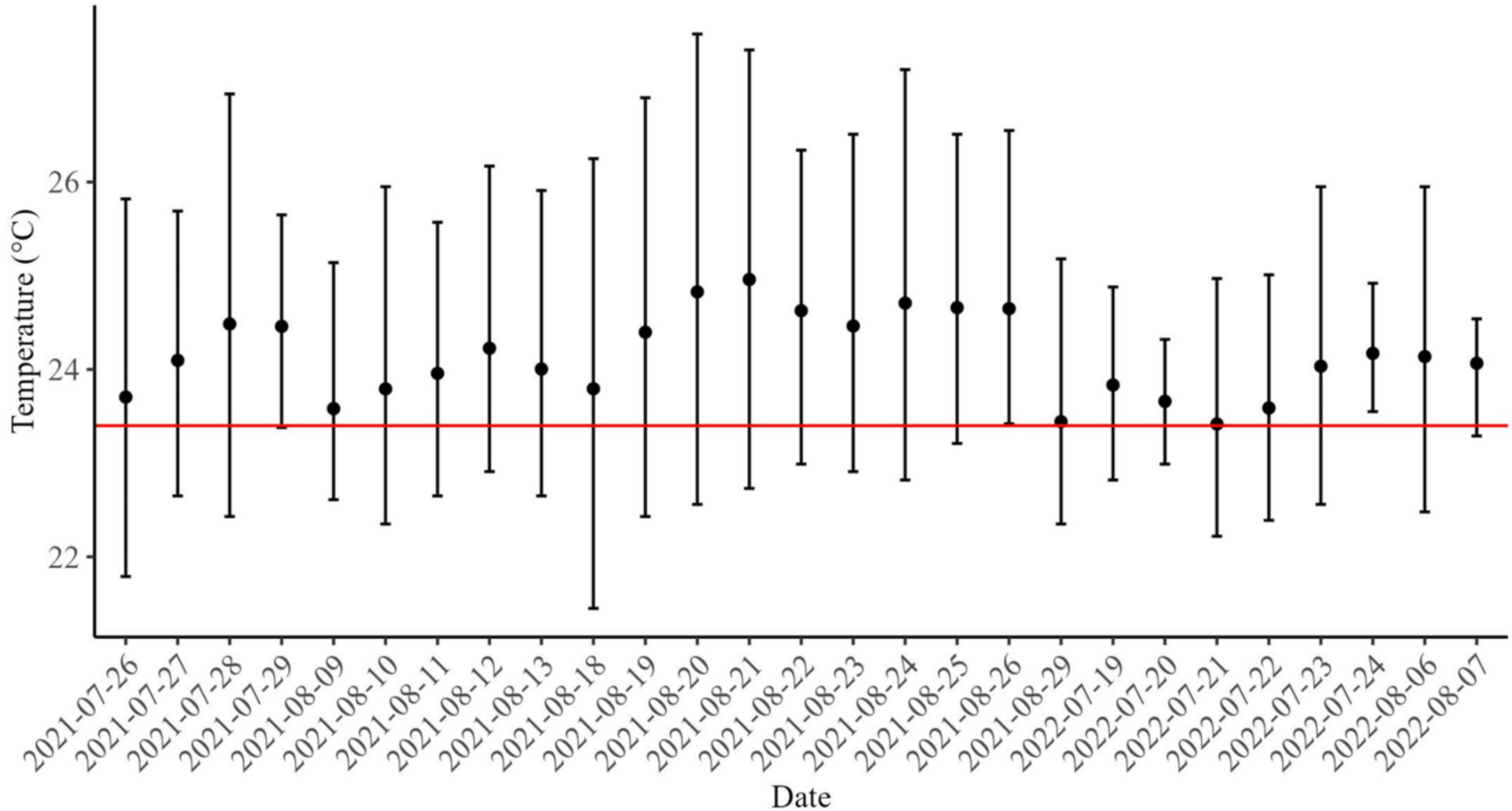


FIGURE 7. Diel temperature variation for each day in which the mean daily temperature reached 23.4°C, the upper limit for positive growth for Brook Trout (denoted by red line), or higher at the Below Chub Lake station, including heatwave events July 26–29, 2021; August 09–13, 2021; August 18–26, 2021; July 19–24, 2022; and August 06–07, 2022. The solid black circle represents the mean temperature for the given day with the upper whisker the maximum and lower whisker the minimum daily temperature.

Discussion

This study aimed to address perceived declines of Brook and Brown trout during the 2018 and 2019 fishing season by examining the thermal regime of the NBAS through the use of point-based temperature monitoring. Spatial distribution of fish on a local scale and population densities may vary due to additional factors not examined in this study including fish seeking thermal refugia in other areas such as smaller tributaries with heavy canopy cover and/or increased cold water seepages, potential low recruitment, inter- and intra-specific competition between Brook and Brown trout, and changes in seasonal flow regimes. Station A, Below Chub Lake, exceeded the Brook Trout ULPG 27 separate days during the two-year study period, with the greatest difference between the mean daily temperature and the ULPG occurring one day after the highest maximum water temperature (27.6°C) was reached (Figure 7). This occurred during a nine-day limnological heat wave. A second limnological heat wave was observed in 2022 and was associated with the highest minimum water temperature that was observed (23.6°C). This station, located near the outflow of Chub Lake, is influenced by the lentic waters of the lake which is a likely cause of warmer waters in this region. The lentic influence is reduced through an influx of cooler ground water in the downstream reaches.

The mean preferred temperature range of Brook Trout has been described as 10.6–17.1°C (Baird and Krueger 2003; Durhack et al. 2021; Goyer et al. 2014). Even with a rather wide-ranging thermal preference, the NBAS exceeded conditions favored by Brook Trout at the stations sampled. During times of limnological heat waves, fish are likely to exhibit migratory behavior to seek out thermal refugia, underscoring the importance of thermal refuge in the NBAS and its tributaries.

Brook and Brown trout, along with other salmonid species, are known to seek out thermal refugia when water temperatures rise (Baird and Krueger 2003; Biro 1998; Wilbur et al. 2020; Petty et al. 2012). The availability of cold water thermal refugia is critical to the ongoing sustainability of native Brook Trout populations in the NBAS and its tributaries. Brook Trout have been shown to increase movement within streams when the ambient water temperature exceeds 18°C (Petty et al. 2012). Of the 61,390 temperature readings, a total of 23,267 (37.9%) were greater than 18°C. Temperatures exceeded the optimal growth threshold for Brook Trout 57.98% of the time during which samples were collected and 28.63% of the time for Brown Trout. While these temperatures may not induce an increase in movement, physiological changes such as an increase in metabolic rate may begin to impact the fish (Durhack et al. 2021). Further, the ULPG threshold was exceeded in 3.37% of the daily observations, indicating an even greater amount of stress on the fish, potentially limiting growth and survival. During limnological heatwaves, mean daily temperatures and diel fluctuations from minima to maxima, exceeded the ULPG for Brook Trout (Figure 7) resulting in consecutive days deemed unsuitable for Brook Trout at the Below Chub Lake station. Minimum daily temperatures were also found to be above the thermal optima for Brook Trout during these events (Figure 7), indicating that diel temperature fluctuations did not offer reprieve from the warm water, further indicating a need to seek thermal refugia. These data highlight the importance of the availability of thermal refugia within the tributaries to offset these impacts.

Brook Trout have a lower thermal optimal range than Brown Trout and may serve as a sentinel species for a shifting or changing ecosystem and their monitoring should be prioritized. Petty et al. (2012) found that Brook Trout did not inhabit waters exceeding 19.5°C in an Appalachian stream complex. Water temperatures at the nine NBAS stations regularly exceeded this temperature in 2021 and 2022. If thermally induced behavior of Brook Trout is similar between NBAS and Appalachian streams, fish would be likely to exhibit a high degree of movement within the available waters to avoid unsuitable water temperatures, potentially providing the perception of an absence of fish in the waters primarily targeted by fishers. Thermally induced migration of Brook Trout may increase the likelihood of spatial overlap with likely competitors, compounding the impact of reduced habitat.

When water temperatures exceed 18.0°C, Brook Trout are expected to begin actively seeking thermal refugia. These habitats may begin to experience crowding as temperatures rise due to an influx of fish (Petty et al. 2012). Limitations of suitable habitat during times of limnological warming events will likely be exacerbated during high temperature events when both Brook and Brown trout seek thermal refuge (Johnson et al. 2024). During these times, more aggressive competitors such as Brown Trout are likely to outcompete others. Further, warmer stream temperatures are likely to expand the habitat available to Brown Trout, encroaching on habitat refugia occupied by native Brook Trout. This has the potential to negatively affect Brook Trout growth and survival (Valerie and Daniels 2021). Olson et al. (2024) found a positive relationship between Brown Trout and summer stream temperature as related to suppression of Brook Trout and active removal of Brown Trout resulted in increased Brook Trout biomass and density. This supports the concept that under warming water conditions, the impacts of competition with non-native Brown Trout are amplified. Relief from competitive pressures, especially under warming conditions, may allow Brook Trout to utilize thermal refugia and increase potential recruitment success. Maintaining and potentially increasing the availability of cold-water thermal refugia will be beneficial to the longevity of Brook Trout populations in NBAS. Alternatively, mitigating warming waters could benefit Brook Trout.

Physiological processes may also be affected by increased water temperature including increased metabolic rate, plasma glucose, cortisol, and heat shock proteins (Chadwick et al. 2015; Durhack et al. 2021). Chadwick et al. (2015) found increased plasma glucose, cortisol, and gill heat shock protein concentrations when the mean daily temperature exceeded 21.0°C. Wehrly et al. (2007) found occurrences of Brook Trout to be rare once mean daily temperatures exceeded 21.0°C for 60 days or more per year, which may be linked to physiological stressors depleting the population and/or avoidance of warm waters when thermal refugia is present. During the period of study on the NBAS, 16 days in 2021 and 10 days in 2022 had a mean daily temperature > 21.0°C, indicating that while the temperature is fluctuating and exceeds key thresholds frequently, Brook Trout should not be considered rare in this system. However, during times when the water temperature exceeds 21.0°C, Brook Trout would need to seek thermal refuge or physiological impacts would occur. Catch-and-release angling also has physiological impacts to fish which can be affected by environmental factors such as increased water temperature. Recovery period from an angling event increases with water temperature (Gingerich et al. 2007; Gale et al. 2011; Brownscombe et al. 2022). The NBAS and surrounding waters are heavily fished with many anglers practicing catch-and-release. Brownscombe et al. (2022) found water temperatures greater than 19.5°C increased recovery time and impairment in

Brook Trout under simulated catch-and-release angling. As salmonids are regularly sought after as game fish, it is important to understand the cumulative effects of stressors and their relationship to increased water temperatures.

Salmonid growth and survival are dependent on the ability of the fish to access water in which temperatures remain within a range conducive to growth, with little deviations from critical thermal thresholds. The relationship between growth, survival, and stream temperature are dependent on the degree of warming and exceeding upper limit thresholds. Once water temperature exceeds upper limits, or instances with rapid increases in temperature, the relationship transitions from positive to negative (Hokanson et al. 1977; Pisano et al. 2019; Xu et al. 2010). High degrees of stochasticity in temperature variation negatively affect growth of age-0 Brook Trout (Pisano et al. 2019). Marten (1992) found incubation temperature affects Brook Trout survival with extremely high or low temperatures resulting in higher mortality. Bašić et al. (2018) found warm temperature anomalies to have positive effects on young, age-0 European Grayling *Thymallus thymallus*, but only to a threshold of 13.5°C after which warming had negative effects on growth and survival. Age-0 Arctic Grayling *Thymallus arcticus* weight was found to decrease under higher flow conditions in an Arctic stream in Alaska, however temperature was positively correlated with growth (Deegan et al. 1999), albeit likely due to a relatively low temperature threshold. This further supports the concept that variation in stream discharge and temperature fluctuations can impact growth and survival of salmonids, leading to declining recruitment. Dramatic changes in ambient temperatures and precipitation may negatively affect stream temperatures and discharge in the absence of thermal refugia. Climate change has the potential to increase annual variability in seasonal temperature regimes and across shorter periods of time (days to weeks), from abnormally warm to abnormally cold for example, as compared to the historic regime, a trend that is unfolding across much of North America (Vincze et al. 2017).

Climate change has the potential to increase stream water temperatures, even those predominantly thermoregulated by groundwater such as the NBAS. Stations with the highest degree of temperature stress should be assessed further to examine if other ecological factors may be contributing to warmer temperatures. The upstream stations, Below Chub Lake, Turtle Creek, and The Ford, are likely impacted by lakes and wetland reaches upstream and before the warmer waters are diluted by influxes of groundwater within the mainstem of the NBAS and associated tributaries. Other impacts may include shallow, wide reaches of the river. For example, the cross-section of The Ford and Twin Bridge stations are relatively wide and shallow. This may contribute to thermal radiation increasing warming due to decreased areas of the river shaded by overhead canopy cover and increased solar radiation throughout the entire water column in the absence of deep zones (Ebersole et al. 2003). The forest surrounding the NBAS was historically heavily impacted by logging, leaving a wider stream channel with a relatively young riparian zone. Deep pools, groundwater seeps, and other forms of cover and thermal refugia represent critical habitat to salmonids when waters warm (Petty et al. 2012). Absence or limits of such features are likely to limit the success of salmonids within the watershed (Quilbé et al 2025). Efforts should be taken to address these impacts to ensure a resilient stream ecosystem with the ability to buffer the impacts of a warming climate.

Ongoing monitoring of the NBAS and its watershed could support future decisions for the NBAS intended to mitigate the impacts of climate change such as warming water, changes in precipitation, and altered flow regimes. Consideration should be given to stream water temperature, flow, land use and canopy cover, and to the often overlooked hyporheic zone. This list is not exhaustive, representing a suite of variables that affect stream water thermal regimes. The hyporheic zone acts as an interface between the groundwater and surface waters with impacts on overall stream health from nutrient concentration to water temperature (Boulton et al. 2010). Streams dominated by groundwater are often buffered by the impacts of warming ambient air temperatures, however localized temperature fluctuations are observed, often during the warmest times of the day or associated with heatwave events (Kanno et al. 2014). Young salmonids will readily seek out groundwater upwellings to escape unsuitably warm waters (Saltveit and Brabrand 2013). Hyporheic zones and groundwater influxes are critical habitat components that can provide thermal refugia with the exchange of colder groundwater and warmer surface waters. Changes in land use and decreasing canopy cover may also increase overall stream water temperatures, affecting invertebrate and vertebrate populations (Johnson et al. 2024). Warmer waters may increase epizootic events and disease prevalence previously suppressed by cooler water temperatures (Karvonen et al. 2010; Stene et al. 2014; Miller et al. 2014; Bruneaux et al. 2017; Mitro 2016; Sandvik et al. 2021). Increased water temperatures, low flow, and stress due to increased Brown Trout, led to an increase in the ectoparasitic infection of Brook Trout by *Salmincola edwardsii*, nearly extirpating Brook Trout in a Wisconsin stream within a single year (Mitro 2016).

The inclusion of the full dataset for Twin Bridge in 2021 provided insight into the importance of temperature monitoring in months not regularly deemed “months of concern” (summer) for warming waters (Figure 5). Warming events have increasingly occurred in these “off months” both in spring and autumn, as shown by the increased frequency of degrees of temperature stress at the Twin Bridge station in 2021 as compared to stations nearby (Figure 5). In addition to heat stress, cold stress may also affect fish such that temperature monitoring in winter months is also warranted. Efforts should be taken to increase ambient stream water temperature monitoring year-round and determine the size and frequency of thermal refugia within the NBAS watershed to aid in understanding species interactions and to support management of the salmonid populations within the watershed.

Disruptions in the once stable stream temperature and discharge regime are likely to result in decreased recruitment, altered growth, and decreased survival of young salmonids (Jonsson and Jonsson 2009). Declines in recruitment were noted by Godby (2020) as a potential cause of the declining population of Brook Trout in the NBAS. Warmer temperatures can negatively affect growth and reproductive output (Chadwick et al. 2015). Warmer stream temperatures during incubation are likely to result in a shorter incubation period which may result in ecosystem mismatches during critical ontogenetic shifts such as alevin to fry. Gallagher and Fraser (2023) found Brook Trout hatch earlier in warmer streams with a shorter than average incubation period and produce smaller alevins (Marten 1992). Early life stages of salmonids are less motile and susceptible to being washed out or stranded during times of abnormal stream flow (Zorn and Nuhfer 2007a; Warren et al. 2015) and changes in water temperature reduced hatching success (Saltveit and Brabrand 2013; Sternecker et al. 2014), resulting in declining recruitment over time. Abnormally warm winter temperatures and high stream discharge likely contribute to declining salmonid recruitment (Gregory et al. 2020). Increased summer temperatures and changes in stream discharge have also been shown to reduce survival of age-0 Brook Trout (Xu et al. 2010). This may limit food availability and differing fish community structures which could limit growth and survival with nutrient limitations and potentially increase predation and competition.

The NBAS, a stream renowned for its once strong population of Brook Trout, has historically been held in high regard by fishers. Populations of salmonids, especially Brook Trout, have undergone declines in both population size and growth. Ongoing temperature monitoring on a year-round basis would deepen the understanding of the thermal regime of the NBAS and its impacts to resident salmonids. Monitoring flow regimes of the NBAS could determine if flow is a factor limiting recruitment. Assessing the availability of cold water thermal refugia in both size and frequency throughout the system would aid in understanding species distributions and could increase the effectiveness and robustness of management. Creating and maintaining a resilient ecosystem could buffer the impacts of a warming climate.

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