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RESEARCH ARTICLE

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Spatially variable effects of streamflow on water temperature and thermal sensitivity within a salmon-bearing watershed in interior British Columbia, Canada

Marta E. Ulaski[1] | Luke Warkentin[2] | Sean M. Naman[3] | Jonathan W. Moore[1]

[1]Department of Biological Sciences, Simon Fraser University, Burnaby, British Columbia, Canada

[2]Fisheries and Oceans Canada, Terrace, British Columbia, Canada

[3]Fisheries and Oceans Canada, Freshwater Ecosystems Section. Cultus Lake Labs, Cultus Lake, British Columbia, Canada

Correspondence
Marta E. Ulaski, Department of Biological Sciences, Simon Fraser University, 8888 V5A 1S6 University Drive, Burnaby B.C. Canada.
Email: ulaskimarta@gmail.com

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Abstract

Warming temperatures can have negative consequences for aquatic organisms, especially cold-adapted fishes such as Pacific salmon. The magnitude of warming is related to the thermal sensitivity of streams in salmon-bearing watersheds (i.e., change in stream temperature for every 1°C increase in air temperature), which can vary based on several factors including streamflow. Management actions to increase streamflow may therefore benefit salmon by decreasing thermal sensitivity. However, the effects of streamflow on thermal sensitivity are often complex, as the temperature of flow inputs can directly increase or decrease temperatures. This study aimed to disentangle the influence of streamflow on thermal sensitivity and stream temperature over 4 years in the Nicola River, a regulated semiarid watershed in south-central British Columbia, Canada. A statistical modeling approach was used to estimate streamflow effects on stream temperatures and thermal sensitivity (i.e., relationship of regional air temperature to stream temperature) at 12 sites from 2018 to 2021. Streamflow had a variable influence on stream temperatures across the watershed via both direct effects and by modulating thermal sensitivity. At a given site, streamflow was generally negatively associated with summer daily mean stream temperature, but the magnitude of its influence varied among locations and years. The influence of streamflow on thermal sensitivity was also highly variable both spatially and temporally. The analysis suggests that there may be complex relationships between streamflow, stream temperature, and thermal sensitivity, which complicates the efficacy of flow as a lever to mitigate high temperatures in regulated systems.

KEYWORDS
flow, management, Pacific salmon, river, temperature, thermal sensitivity

1 | INTRODUCTION

Temperature is rapidly changing due to the effects of global change and is a key environmental variable in aquatic ecosystems (Poole & Berman, 2001; Webb et al., 1996). Species vary in their sensitivity to water temperatures and mortality can occur if temperatures exceed thermal limits (Bennett et al., 2018). Thus, changes in thermal regimes can alter species abundance and distribution due to species-specific temperature tolerance ranges (Niedrist & Füreder, 2020; Wenger et al., 2011). For Pacific salmon *Oncorhynchus* spp., excessively warm waters can inhibit migration, increase susceptibility to disease and predation, and cause direct mortality (Martins et al., 2011; Richter & Kolmes, 2005).

The temperature of streams and rivers is a function of several factors but net radiation (i.e., balance between incoming solar radiation and outgoing long-wave radiation) typically has the greatest influence (Brown, 1969; Webb & Zahng, 1997). Heat lost or gained through evaporation or condensation, the transfer of heat between water and air, heat added through fluid friction, and conduction of heat between the stream and stream bed also contribute to the temperature of streams and rivers. In addition, temperatures can fluctuate due to heat transfer from precipitation, tributary, and groundwater inputs. The importance of each component of the river heat budget can vary spatially and temporally due to the influence of stream characteristics. For example, shading by channel banks and riparian vegetation can reduce the amount of radiation that reaches a stream. The effect of net radiation on stream temperatures can be described as thermal sensitivity and is often measured as the change in water temperature for every 1°C increase in air temperature (Mayer, 2012). Thermal sensitivity varies naturally within and among watersheds (Nelitz et al., 2007) due to the variable influences of groundwater, stream shading, elevation, watershed area, stream width, and snowmelt (Beaufort et al., 2020; Cline et al., 2020; Lisi et al., 2015; Mauger et al., 2017).

Stream temperature and thermal sensitivity are increasing due to human-induced climate warming as well as local or regional impacts on land and water (Kaushal et al., 2010; Wild et al., 2008). For instance, the removal of riparian vegetation from forestry increases the amount of short-wave solar radiation reaching streams resulting in higher thermal sensitivity and warmer stream temperatures (Binkley & Brown, 1993; Moore et al., 2005). Similarly, upland vegetation removal decreases groundwater infiltration on hill slopes, and pumping wells for irrigation and municipal water sources decrease groundwater discharge into streams, also resulting in increased thermal sensitivity and warming (Hester & Doye, 2011; Poole & Berman, 2001). While these human-caused impacts on temperatures challenge the management of cold-water adapted taxa, they also highlight potential management levers to promote thermal resilience. For example, restoring riparian vegetation can decrease daily maximum stream temperatures by 6°C or more (Wondzell et al., 2019).

Altering streamflow may be a particularly effective management lever for decreasing the thermal sensitivity of streams (Olden & Naiman, 2010; Sinokrot & Gulliver, 2000). In general, increasing streamflows elevates thermal capacity and reduces residence time, leading to decreased thermal sensitivity (Smith & Lavis, 1975; Webb et al., 1996). There are several levers to control streamflow. First, streamflow can be directly altered in regulated systems by storing water during cooler periods and augmenting flow during the warmest months of the summer (Sinokrot et al., 1995). Second, low streamflow could also be mitigated by decreasing the number of licensed water extractions (Poole & Berman, 2001). Third, modifying forestry practices can indirectly increase summer flows. Clear-cutting can cause accelerated rates of snowmelt, leading to an earlier onset of the post-freshet recession towards baseflow and lower daily summer streamflow. After harvest, young regrowing forests of uniform age can reduce summer baseflow due to their high evapotranspiration relative to mixed-age or old-growth forests (Gronsdahl et al., 2019; Perry & Jones, 2017; Winkler et al., 2017). However, the effects of streamflow on stream temperature are complex because the temperature of streamflow inputs can directly transfer heat to downstream reaches (Mohseni & Stefan, 1999). Temperature-flow relationships are therefore variable and dependent on the relative influence of contrasting water sources (e.g., groundwater, surface flow, or reservoir releases; Mayer, 2012). For instance, water released from reservoirs to downstream stream reaches can become progressively warmer during summer months due to increased residence time, thermal inertia, and thermal stratification of the stored water (Webb & Walling, 1997). As a result, increased temperatures are often observed downstream of small surface-release dams (Zaidel et al., 2021). Understanding the intricacies of the effects of streamflow on stream temperature is essential for informing effective management to balance land and water use with the requirements of aquatic organisms.

Disentangling the factors that influence stream temperature and temperature sensitivity is particularly urgent in watersheds where flows and temperatures are posing risks to fish of conservation priority (Warkentin, 2022). The Nicola River basin in south-central British Columbia, Canada represents a semi-regulated, interior watershed that is facing multiple stressors from human activities and climate change. The Nicola River watershed also supports populations of imperiled Chinook salmon, coho salmon, and steelhead (COSEWIC, 2020), which migrate upriver to spawn during the summer when streamflows are at their lowest and stream temperatures often exceed critical thresholds associated with migratory and spawning success (Richter & Kolmes, 2005; Warkentin, 2022). The objectives of this paper were to estimate the extent to which flow mediates the sensitivity of summer stream temperatures to air temperatures in important Pacific salmon habitat. Understanding how streamflow influences water temperatures could help inform water management strategies. For example, releasing additional water could potentially decrease thermal sensitivity in streams when air temperatures are high. We hypothesize that streamflow is an important predictor of summer stream temperature and influences thermal sensitivity in the Nicola River basin. We also hypothesize that the magnitude of the influence of streamflow on thermal sensitivity varies spatially in the watershed because of differences in the temperature and amount of surface and groundwater inputs.

2 | METHODS

2.1 | Study area

The Nicola River watershed is in south-central British Columbia and is a part of the traditional, ancestral, and unceded territories of the

Nlaka'pamux and Syilx Nations. The Nicola River is a tributary to the Thompson River, which flows into the Fraser River at Lytton in British Columbia, Canada. Several tributaries drain into the Nicola River including the Coldwater River, Guichon Creek, Spius Creek, and Quilchena Creek, with a total drainage area of 7184 km^2. Several large lakes drain into Nicola River and its tributaries including Mamit, Stump, Chapperon, Douglas, and Nicola Lake. A small dam at the outflow of Nicola Lake is used for water storage (for agriculture and conservation flows) and to supplement summer streamflow for Pacific salmon. The flow regime of the Nicola River is driven by snowmelt, with a large spring freshet that usually peaks in late May or early June. The summer climate in the region is characterized as hot and dry with daily maximum air temperatures often exceeding 30°C and ~25–30 mm of average monthly precipitation from July to September. Typically, the lowest flows (i.e., ~10% of mean annual flows) occur in August and September (Rood & Hamilton, 1995). The watershed supports imperiled stream-rearing Chinook salmon *O. tshawytscha*, coho salmon *O. kisutch*, steelhead *O. mykiss*, and bull trout *Salvelinus confluentus*. Nicola River Chinook salmon have been in steep decline in recent years and were recently assessed as endangered by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC, 2020). Environmental conditions in the Nicola River basin have drastically changed over the past century including rising summer air temperatures, increased rainfall, and reductions in summer streamflow (Warkentin, 2022). Water allocations during low flows in the summer are high with licensed water demand at approximately 50% of mean August flow (Walthers & Nener, 1997). In addition, logging in the watershed has expanded substantially with 17% of the watershed logged (~20,000 ha) within the last two decades.

2.2 | Data collection

Stream temperatures at ~50 sites throughout the Nicola River watershed were measured from 2018 to 2021 and a subset of 12 sites were used for the analyses due to their proximity to streamflow gauges (Figure 1 and Table 1; Chezik et al., 2017; Warkentin, 2020). The temperature monitoring program was motivated and informed by the Nicola Watershed Collaborative, including specific guidance and support from partners from First Nations, Provincial agencies, and Fisheries and Oceans Canada. Personnel of the Salmon Watersheds Lab of Simon Fraser University installed temperature data loggers (Onset, Bourne, MA; HOBO Pendant and Tidbit) in late August–September of 2017 and one logger in Nicola River at Norgaards in August 2018 (Table 1). Loggers were primarily placed in deep pools sheltered by boulders to avoid dewatering and disturbance during floods. Aircraft cable was used to attach each logger, which was housed in white PVC cases, to a boulder, tree, or anchor bolt with climbing hanger installed into a boulder. Stream temperature was recorded every hour or every other hour. Loggers were installed year-round and data were downloaded annually in August–September from 2017 to 2019 and 2021 when loggers were retrieved and re-installed. We replaced loggers that were missing because of either flooding or tampering (Table 1).

We visually inspected stream temperature data and removed periods where temperature loggers were dewatered. Dewatering events were characterized by a sudden large increase in recorded temperature and an increase in the magnitude of diurnal temperature fluctuations. We calculated daily mean temperatures (°C) from hourly recordings of stream temperature at each site. We designated July 1–September 30 as the summer season and focused on this period throughout the analysis. Several sites had incomplete water

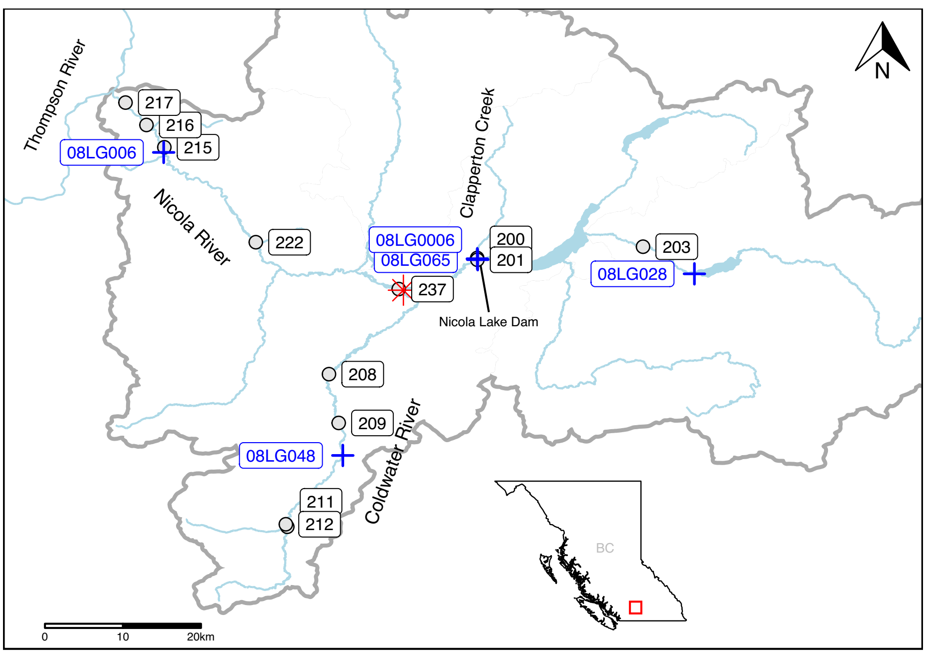

FIGURE 1 Map of the Nicola River watershed with the locations of numbered temperature monitoring sites depicted by grey points and white labels. Locations of labeled flow gauges are indicated by blue plus symbols and blue labels. Merritt weather stations are represented by the red star. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Locations of temperature monitoring sites, nearby hydrometric stations, and years when data were available for each site in the Nicola River watershed, British Columbia, Canada.

Site	Location	Hydrometric station	Hydrometric data source	Latitude	Longitude	Years	Temperature data
200	Clapperton Creek at the mouth	08LG0006	Aquarius data portal	50.16476	−120.6697	2018	No; dewatered
						2019–2021	Yes
201	Nicola River above Clapperton Creek	08LG065	Environment and Climate Change Canada	50.16199	−120.6694	2018–2021	Yes
203	Nicola River above Nicola Lake	08LG028	Environment and Climate Change Canada	50.18258	−120.3750	2018	No; missing logger
						2019–2021	Yes
208	Coldwater River above Patchett Road	08LG048	Environment and Climate Change Canada	49.98209	−120.9331	2018–2021	Yes
209	Coldwater River under Gillis Road	08LG048	Environment and Climate Change Canada	49.90536	−120.9158	2018	No; dewatered
						2019–2021	Yes
211	Coldwater River above Juliet Creek	08LG048	Environment and Climate Change Canada	49.74206	−121.0071	2018–2021	Yes
212	Coldwater River below Juliet Creek	08LG048	Environment and Climate Change Canada	49.7460	−121.0097	2018–2021	Yes
215	Nicola River below Skeikut Creek	08LG006	Environment and Climate Change Canada	50.33898	−121.2257	2018, 2020–2021	No; missing loggers
						2019	Yes
216	Nicola River below Kloklowuck Creek	08LG006	Environment and Climate Change Canada	50.37406	−121.2574	2018–2019	Yes
						2020–2021	No; missing logger
217	Nicola River near Spences Bridge	08LG006	Environment and Climate Change Canada	50.40926	−121.2947	2018, 2020–2021	No; missing loggers
						2019	Yes
222	Nicola River at Shackelly Creek	08LG006	Environment and Climate Change Canada	50.18963	−121.0631	2018–2019	Yes
						2020–2021	No; missing logger
237	Nicola River at Norgaards	08LG0006, 08LG065, 08LG048	Environment and Climate Change Canada	50.11597	−120.8091	2018	No; installed in August
						2019	Yes
						2020–2021	No; damaged logger

temperature records due to missing temperature loggers or dewatering events. Therefore, we only included sites and years with complete (100% of days) summer stream temperatures from July 1 to August 30 (Table 1).

Daily streamflow data ($m^3\ s^{-1}$) are recorded at several streamflow gauges throughout the Nicola River basin, which are operated by Water Survey Canada and BC Ministry of Land, Water and Resource Stewardship. We downloaded streamflow data using the R programming language and the tidyhydat package (Albers, 2017). Streamflow data for Clapperton Creek were accessed from the Aquarius web portal (https://aqrt.nrs.gov.bc.ca/). Stream temperature sites were matched to the closest streamflow gauge using arcGIS software (Esri; Redlands, CA) and verified through visual inspection. At site 237 (i.e., Nicola River at Norgaards), we estimated streamflow by summing daily discharge from Nicola Lake, Clapperton Creek, and Coldwater River at Merritt. Streamflow data associated with each temperature site represent an approximation of daily discharge at each location rather than an absolute measure of flow where stream temperatures were measured.

Daily mean regional air temperatures (°C) are recorded at the Merritt and Merritt STP stations by Environment and Climate Change Canada (https://climate.weather.gc.ca/historical_data/) and are located at the approximate center of the Nicola River watershed (Figure 1). We primarily used air temperatures recorded by the Merritt STP station, but air temperatures from the Merritt station were used for 2020 and 2021 due to missing records from the Merritt STP station. However, both stations are in close proximity (i.e., within 1.7 km and a difference of 18 m in elevation) and when records overlap air temperatures are highly correlated at the two stations ($R^2 = 0.99$).

2.3 | Data analysis

We estimated the influence of streamflow on both thermal sensitivity and water temperature in the Nicola River watershed using a statistical modeling approach. Linear models were fit to observe daily mean stream temperature at each location using predictor variables of daily mean air temperature (i.e., climate sensitivity), daily streamflow, and an interaction between air temperature and flow (i.e., effect of flow on climate sensitivity; Table S1 in Supplementary Material). Due to the inherently autocorrelated nature of streamflow temperature data, we included the response variable (i.e., observed stream temperature) at the previous time step as a predictor in each model (i.e., autoregressive model; Brockwell & Davis, 2002; Hostetler, 1991; Sohrabi et al., 2017). We fit a separate model for each location and year because: (a) we expected a different relationship between flow, air temperature, and stream temperature for each site and year and (b) data were not available for the same years at each site (Hilderbrand et al., 2014). Daily mean air temperature, daily flow, and lagged stream temperature were standardized for each location to a mean of zero and standard deviation of one to ease interpretation of the relative magnitude of main effects and their interactions within and among sites and years (Schielzeth, 2010). Thirty-two global models were fit, with each global model representing a unique site-year combination. Alternative models for each location and year were compared using Akaike's Information Criterion for small sample sizes (AIC_c; Table S1 in Supplementary Material; Burnham & Anderson, 2002). The suite of models fit for each location and year was defined as,

$$\widehat{W} = \alpha + \beta_{\text{air}}\text{Air} + \beta_{\text{flow}}\text{Flow} + \beta_{\text{air}\times\text{flow}}\text{Air} \times \text{Flow} + \beta_{\text{lag}}W_{t-1} + \varepsilon, \quad (1)$$

$$\widehat{W} = \alpha + \beta_{\text{air}}\text{Air} + \beta_{\text{flow}}\text{Flow} + \beta_{\text{lag}}W_{t-1} + \varepsilon, \quad (2)$$

$$\widehat{W} = \alpha + \beta_{\text{air}}\text{Air} + \beta_{\text{lag}}W_{t-1} + \varepsilon, \quad (3)$$

$$\widehat{W} = \alpha + \beta_{\text{lag}}W_{t-1} + \varepsilon, \quad (4)$$

where $\widehat{W}$ is predicted mean daily stream temperature and α is the model intercept. The parameters β_{air}, β_{flow}, $\beta_{\text{air}\times\text{flow}}$, and β_{lag} indicate the estimated effects of the predictor variables Air, Flow, Air × Flow, and W_{t-1} (mean daily stream temperature at the previous time step), respectively. For each suite of models, we selected the model with the lowest AIC_c (Burnham & Anderson, 2002). Parameters and their 85% CIs for each predictor variable were then estimated (Arnold, 2010). We also backtransformed parameter estimates to compare unstandardized effect sizes in the units originally measured for each predictor variable. Effects were visualized using partial regression plots for models that included the interaction between air temperature and flow. All analyses were performed using R programming software (R Core Team, 2018).

3 | RESULTS

Stream temperatures from July to September varied among locations and years throughout the Nicola River basin (Table 2 and Figure 2). Average summer daily mean stream temperatures were 13.5°C (range = 4.1–20.6°C) at the Coldwater River sites, 18.5°C (range = 10.8–23.1°C) at the Nicola River mainstem sites, 18.0°C (range = 9.1–25.8°C) at the upper Nicola River sites, and 14.2°C (range = 6.5–20.1°C) at Clapperton Creek. Daily discharge from July to September also varied among locations and years (Table 2 and Figure 2). Average summer daily discharge was 1.59 m^3s^{-1} (range = 0.38–14.2 m^3s^{-1}) at the Coldwater River sites, 8.9 m^3s^{-1} (range = 2.51–30.0 m^3s^{-1}) at the Nicola River mainstem sites, 3.22 m^3s^{-1} (range = 0.03–23.5 m^3s^{-1}) at the upper Nicola River sites, and 0.3 m^3s^{-1} (range = 0.01–1.89 m^3s^{-1}) at Clapperton Creek. Average daily mean air temperatures during the summer study period at Merritt, BC were similar among years and varied from 17.0 to 17.7°C (Figure 2). Daily mean air temperature varied from 7.0 to 27.5°C in 2018, 5.8 to 23.8°C in 2019, 8.6 to 24.7°C in 2020, and 8.9 to 25.8°C in 2021, which included an extreme 1000-year heat event in late June 2021 (Overland, 2021). In general, average daily mean air temperatures were warmer in July and cooler in September. The weight of evidence from model selection using AIC_c resulted in varying models predicting stream temperature for each location and year. All models fit the observed data well ($R^2 > 0.87$). Each selected model included both mean daily air temperature and observed mean daily stream temperature at the previous time step after model selection (Figure 3 and Table S1 in Supplementary Material). However, daily discharge and the interaction of air temperature and streamflow were included in the top models for only certain sites and years.

The effect of air temperature on stream temperature (i.e., thermal sensitivity) was always positive and relatively consistent among years and locations (Figure 3). Thus, not surprisingly, days with warmer air temperatures were associated with warmer water temperatures. The average thermal sensitivity among locations and years was 0.29°C·°C^{-1}, which means for every 1°C increase in daily mean air temperature, daily mean stream temperature increases by 0.29°C. The highest thermal sensitivity was found for Nicola River above Nicola Lake in 2021 at 0.41°C·°C^{-1}. Note that thermal sensitivity varied in Nicola River above Nicola Lake in 2021 with streamflow; thus, 0.41°C·°C^{-1} represents thermal sensitivity at average flows in the Nicola River above Nicola Lake in 2021. In

TABLE 2 Mean daily water temperature (°C) and mean daily discharge ($m^3 s^{-1}$) during the summer for location throughout the Nicola River basin from 2018 to 2021.

Site	Location	Year	Number of days	Mean daily water temperature in °C (min–max)	Mean daily discharge in $m^3\ s^{-1}$ (min–max)
200	Clapperton Creek	2019	91	13.4 (6.5–16.2)	0.37 (0.11–1.41)
		2020	91	13.5 (8.6–17.0)	0.32 (0.02–1.89)
		2021	64	16.2 (11.2–20.1)	0.17 (0.01–0.28)
211	Coldwater River above Juliet Creek	2018	91	11.2 (7.0–15.0)	1.47 (0.44–7.42)
		2019	91	11.4 (4.7–14.2)	1.13 (0.38–3.35)
		2020	91	11.3 (6.7–14.4)	2.26 (0.43–14.2)
		2021	68	12.6 (9.4–14.9)	1.42 (0.51–6.85)
208	Coldwater River above Patchett Road	2018	91	15.4 (9.3–20.6)	1.47 (0.44–7.42)
		2019	91	15.8 (6.8–20.0)	1.13 (0.38–3.35)
		2020	91	15.4 (8.7–19.8)	2.26 (0.43–13.2)
		2021	63	17.4 (12.1–20.6)	1.49 (0.54–6.85)
212	Coldwater River below Juliet Creek	2018	91	11.4 (6.8–15.6)	1.47 (0.44–7.42)
		2019	91	11.7 (4.1–14.7)	1.13 (0.38–3.35)
		2020	91	11.5 (6.4–15.2)	2.26 (0.43–14.2)
		2021	68	13.1 (9.6–15.6)	1.42 (0.51–6.85)
209	Coldwater River under Gillis Road	2019	91	15.0 (5.9–18.8)	1.13 (0.38–3.35)
		2020	91	14.5 (7.9–19.4)	2.26 (0.43–14.2)
		2021	63	16.3 (11.2–19.4)	1.49 (0.54–6.85)
203	Nicola River above Nicola Lake	2019	91	16.6 (9.3–19.9)	1.67 (0.34–5.26)
		2020	91	16.7 (10.7–22.1)	3.52 (0.42–15.5)
		2021	64	18.9 (12.7–22.5)	0.43 (0.03–1.82)
237	Nicola River at Norgaards	2019	77	19.1 (13.5–21.8)	5.18 (2.51–9.37)
222	Nicola River at Shackelly Creek	2018	91	17.3 (10.8–22.3)	9.47 (4.87–30.0)
		2019	74	18.8 (15.6–21.7)	9.52 (4.37–18.0)
216	Nicola River below Kloklwuck Creek	2018	91	17.6 (10.9–23.1)	9.47 (4.87–30.0)
		2019	74	19.0 (15.5–21.7)	9.52 (4.37–18.0)
215	Nicola River below Skeikut Creek	2019	74	19.1 (15.4–22.0)	9.52 (4.37–18.0)
217	Nicola River near Spences Bridge	2019	74	19.4 (15.3–22.5)	9.52 (4.37–18.0)
201	Nicola River above Clapperton Creek	2018	91	18.3 (12.–25.6)	2.95 (1.82–9.05)
		2019	91	18.2 (9.1–21.8)	3.51 (1.95–7.20)
		2020	91	18.0 (11.4–22.7)	6.73 (1.91–23.5)
		2021	64	19.9 (14.5–25.8)	2.77 (1.75–3.20)

Note: Minimum and maximum daily water temperature and mean daily discharge are shown in parentheses.

addition, the standardized coefficients for air temperature and streamflow appear to be opposite of their effects for Nicola River above Nicola Lake in 2021 because standardized streamflow was below mean streamflow (i.e., negative) from 2019 to 2021. Nicola River above Clapperton Creek had the lowest thermal sensitivity at 0.20°C·°C^{-1} in 2021. Thermal sensitivities also varied among years. For locations with multiple years of data, the smallest range among years was 0.005°C·°C^{-1} for the Nicola River below Kloklwuck Creek, and the highest range among years was 0.11°C·°C^{-1} for Nicola River above Nicola Lake.

Streamflow was included as a predictor variable for 20 out of 32 site-year combinations (Table S1). The effect of streamflow on stream temperature was highly variable both spatially and temporally (Figure 3). The mean effect of streamflow was −0.19°C/m^3s^{-1}, indicating a decrease in daily mean stream temperature of 0.19°C for every 1 m^3s^{-1} increase in daily discharge. The largest cooling effect of streamflow on stream temperature was −3.80°C/m^3s^{-1} for Clapperton Creek in 2021 and the smallest cooling effect of streamflow on stream temperature was −0.009°C/m^3s^{-1} for Nicola River above Clapperton Creek in 2018. Streamflow had a positive effect on stream

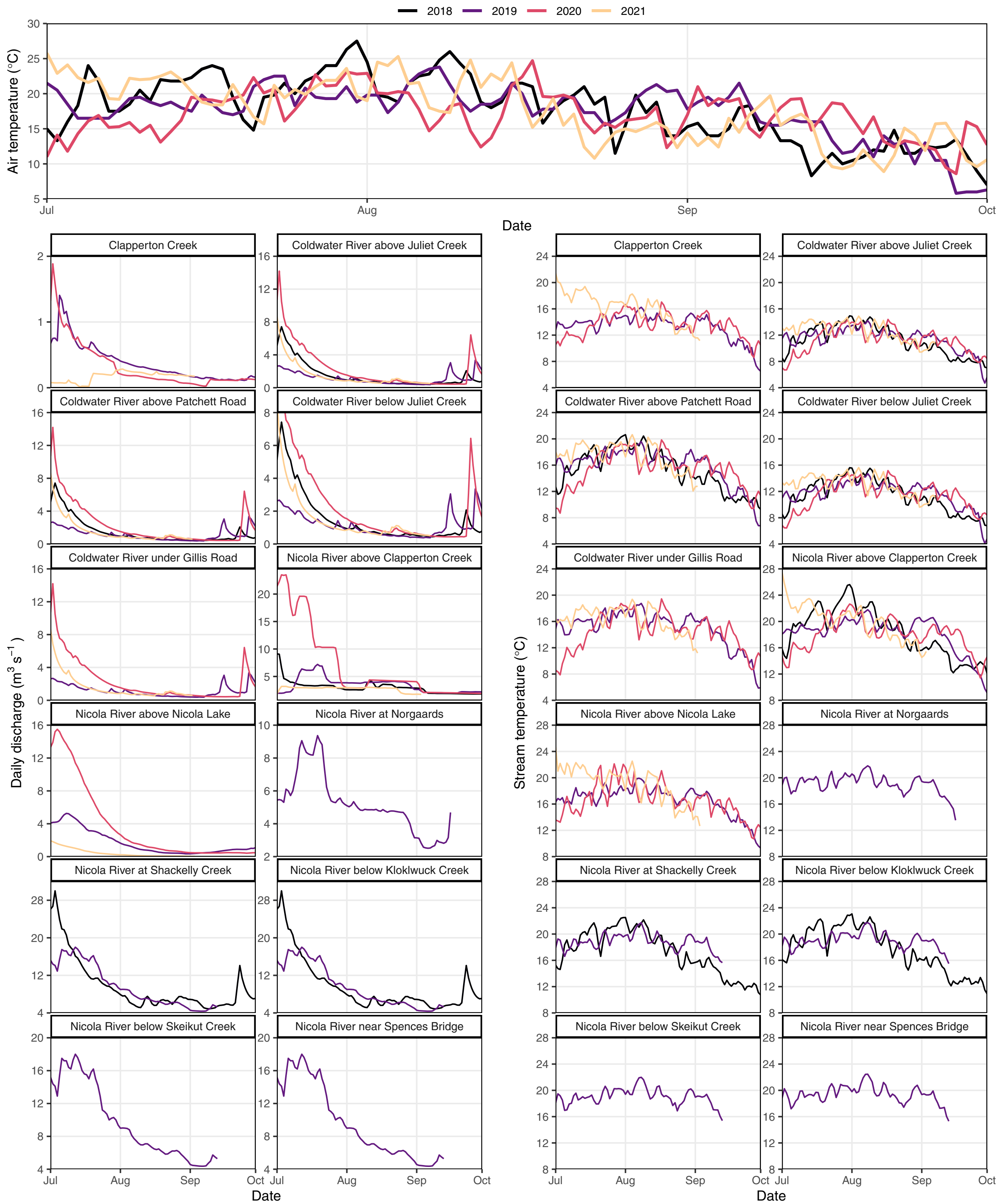

FIGURE 2 Daily mean regional air temperatures, daily flows at nearby hydrometric stations, and daily mean stream temperatures for temperature monitoring sites in the Nicola River basin during July 1–September 30 from 2018 to 2021. [Color figure can be viewed at wileyonlinelibrary.com]

temperature for seven site-year combinations and the highest warming effect of streamflow was 1.67°C/m^{3}s^{-1} for Nicola River above Nicola Lake in 2021. The smallest warming effect was 0.007°C/m^{3}s^{-1} for Nicola River above Clapperton Creek in 2020. For models that included an interaction between air temperature and streamflow, effects represent the influence of streamflow at average air

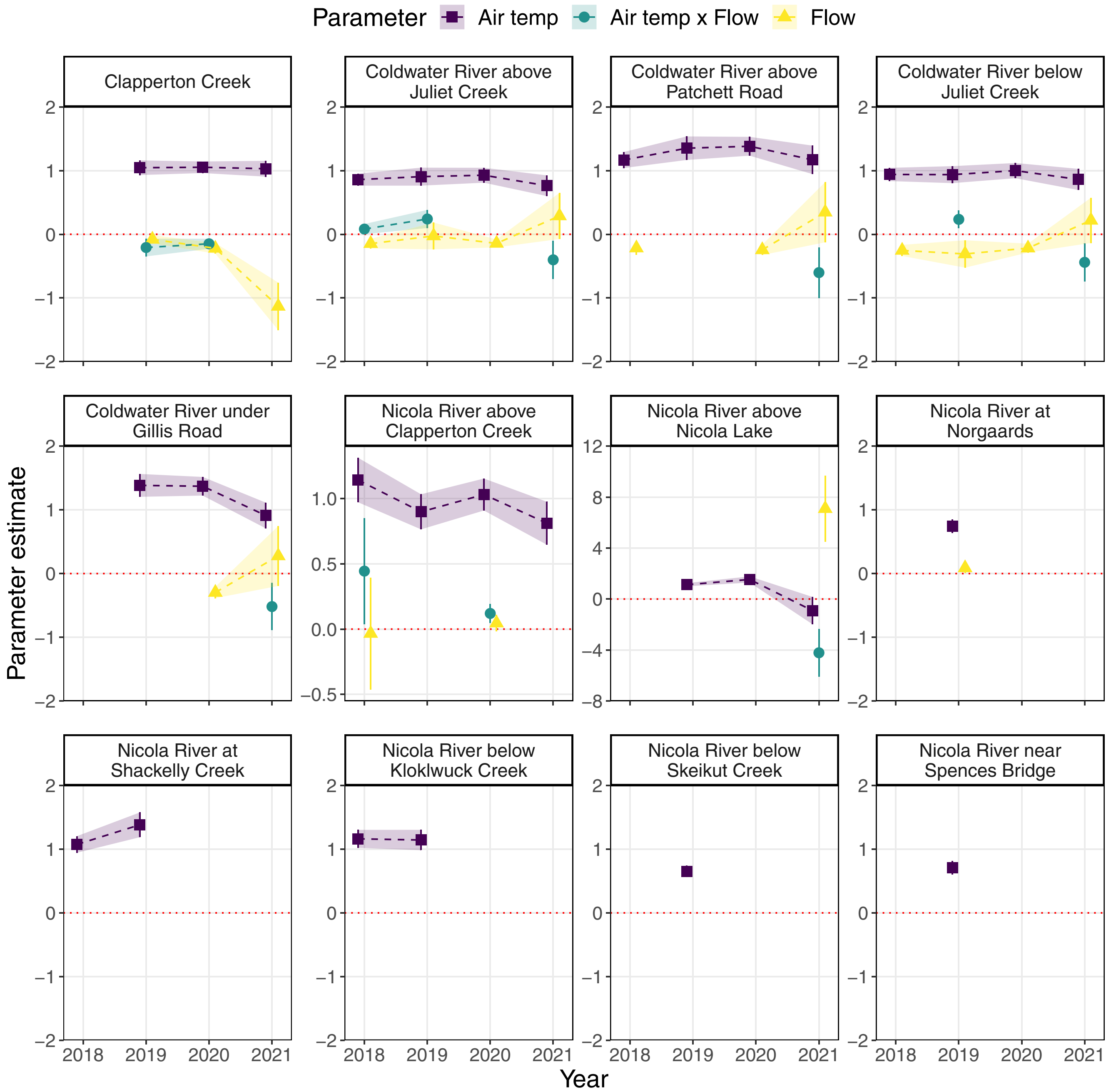

FIGURE 3 Standardized parameter estimates for linear models predicting mean daily stream temperature from July 1 to September 30 at each location in the Nicola River basin and year between 2018 and 2021. Negative daily flow effect values indicate a cooling effect on stream temperature as streamflow increases. A positive air temp × flow interaction means that thermal sensitivity increases at higher flows. By contrast, a negative air temp × flow interaction means that thermal sensitivity decreases at higher flows. Shading and error bars represent 85% CIs. Note that parameter estimates for Nicola River above Nicola Lake are on a different scale. [Color figure can be viewed at wileyonlinelibrary.com]

temperature at that location. The effect of streamflow also varied among years. For locations with multiple years of data, the smallest range among years was 0.02°C/m^{3}s^{-1} for Nicola River above Clapperton Creek, and the highest range among years was 3.60°C/m^{3}s^{-1} for Clapperton Creek.

The effect term representing the interaction between air temperature and streamflow was included for 12 out of 32 site-year combinations. As predicted, thermal sensitivity decreased with increasing streamflow for 7 of the 12 site-year combinations (Figure 3). The highest decrease in thermal sensitivity with increasing streamflow was −0.35°C·°C^{-1}/m^{3}s^{-1} for Nicola River above Nicola Lake in 2021. For example, if streamflow is low (0.05 m^{3}s^{-1}), stream temperature is predicted to increase by 0.46°C for every 1°C increase in air temperature (Figure 4). However, if streamflow is high (1.24 m^{3}s^{-1}), stream temperature will only increase by 0.05°C for every 1°C increase in air temperature. Thus, in these site-year combinations, greater flows led

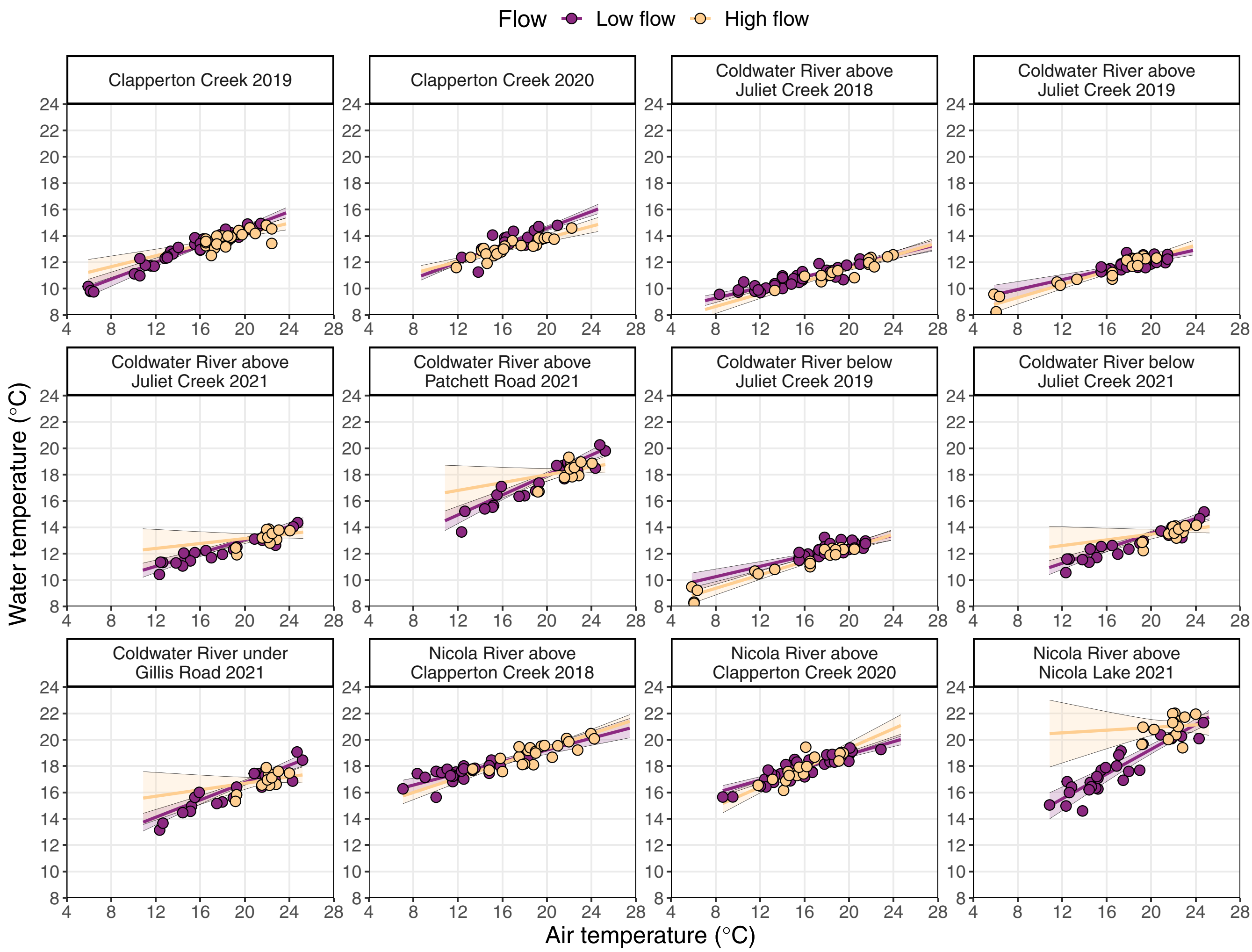

FIGURE 4 Predicted effects of air temperature on summer (July–September) water temperature at temperature monitoring sites in the Nicola River basin at low (orange; 10th percentile) and high (purple; 90th percentile) streamflows for models that included an interaction of air temperature and streamflow after model selection comparing AIC_c values. Shading indicates 95% CIs of effects. Points represent partial residuals that include air temperature and interaction terms plus the mean response. The partial residuals were assigned to the 10th, 50th, and 90th percentile that they were closest to, with residuals that were closest to the 10th (i.e., low flow) and 90th (i.e., high flow) percentiles plotted. [Color figure can be viewed at wileyonlinelibrary.com]

to warmer days having less of an influence on water temperatures. Surprisingly, thermal sensitivity increased with increasing streamflow for five of the 12 site-year combinations. These effects were relatively small. The highest increase in thermal sensitivity with increasing streamflow was $0.03°C \cdot °C^{-1}/m^3s^{-1}$ for Coldwater River above Juliet Creek in 2019. For example, if streamflow is low ($0.43\,m^3s^{-1}$), stream temperature is predicted to increase by 0.18°C for every 1°C increase in air temperature. If streamflow is high ($2.25\,m^3s^{-1}$) then stream temperature is predicted to increase by 0.25°C.

4 | DISCUSSION

Streamflow had a variable influence on stream temperatures across the Nicola River watershed via both direct effects and by modulating thermal sensitivity. At a given site, streamflow was generally negatively associated with summer stream temperature, but the magnitude of its influence varied among locations and years. The influence of streamflow on thermal sensitivity, the relationship between water and air temperature, was also highly variable both spatially and temporally. Our analysis suggests that there may be complex relationships between streamflow, stream temperature, and thermal sensitivity, complicating efforts to mitigate for high temperatures with reservoir management.

We hypothesized that flow would be an important predictor of stream temperature and thermal sensitivity in the Nicola River basin. Our hypothesis was partially supported by the data as streamflow was an important predictor of stream temperature at several locations in the Nicola River basin. Yet, the weight of evidence only supported including the main effect of streamflow in 8 of 12 sites and only seven sites included the interaction of air temperature and streamflow. Further, for locations where streamflow influenced stream temperature or thermal sensitivity, or both, these effects were not consistent across years. We also hypothesized the magnitudes of the effects of streamflow on stream temperature and thermal sensitivity would vary among locations and years. Though there was some variation in the magnitude of the effect of streamflow, the main difference among sites was the direction of the effects of streamflow and its influence on thermal sensitivity. For example, of the 12 models that included an effect term for the interaction of air temperature and streamflow, seven site-years indicated a decrease in thermal sensitivity with higher streamflow and five site-years indicated an increase in thermal sensitivity with higher streamflow (Figure 4).

Streamflow temperature dynamics in the Nicola River watershed were comparable to other studies. First, thermal sensitivity in the Nicola River basin, on average, was $0.29°C·°C^{-1}$ and ranged from $0.20°C·°C^{-1}$ to $0.42°C·°C^{-1}$. These values are relatively low and are similar to those found for small headwater streams with high groundwater input (Tague et al., 2007). Second, several studies have also shown positive relationships between stream temperature and streamflow, which may be the result of warmer surface water diluting cooler groundwater during higher streamflow in the summer (Mayer, 2012). Further investigation of the relative influences of groundwater and surface flow for these sites in the Nicola is needed to support this interpretation. Nevertheless, the predicted reducing effect of flow on thermal sensitivity only occurred at a small subset of sites including Clapperton Creek. The estimated baseflow of Clapperton Creek was very low at approximately $0.05\,m^3s^{-1}$ (unpublished data, Bennett), which could indicate low groundwater influence; thus, increased streamflow could potentially decrease thermal sensitivity by changing the thermal capacity of the stream (Kelleher et al., 2011; Smith & Lavis, 1975).

Our analysis provides a broad look at the relationship between flow and stream temperature in the Nicola River basin, but a few limitations should be considered. First, we only estimated the effect of streamflow during the summer months when variation in streamflow can be relatively low in some years. The lack of contrast in streamflow may have contributed to its variable effect among locations and years. However, the inclusion of streamflow and its influence on thermal sensitivity in each model were not correlated with variation in streamflow for a given location and year. Likely, the variation in the relationship of streamflow, stream temperature, and thermal sensitivity may be a combination of site-specific characteristics (i.e., influence of groundwater) and annual variation in the timing and magnitude of the spring freshet, fall precipitation, and reservoir releases. Additional years of data could support a more complex model and potentially more contrast in streamflow during the summer months may resolve whether streamflow has a strong effect on the thermal sensitivity of streams in the Nicola River basin. Second, streamflow and air temperature were not measured directly at temperature monitoring sites, but instead at nearby streamflow gauges and weather stations (Figure 1 and Table 1). Small changes in streamflow between temperature monitoring sites and gauge stations can occur due to tributary inputs, groundwater inputs or losses, or water withdrawals. Additional error may have been introduced for site 237 (Nicola River at Norgaards) because streamflow was estimated by summing daily discharge from Nicola Lake, Clapperton Creek, and the Coldwater River at Merritt. Using site-specific air temperature instead of regional air temperature may better account for differences in short-wave radiation affected by local characteristics such as aspect and riparian cover (Mauger et al., 2017). Third, for some of the models that included the interaction of air temperature and streamflow, high or low streamflows were not observed across the full range of observed air temperatures (Figure 4). For example, thermal sensitivity for Nicola River above Nicola Lake in 2021 at high streamflows appears to follow the slope of thermal sensitivity at low flows, but the lack of high streamflows at low temperatures introduces a large amount of uncertainty. Fourth, only 1–3 years of stream temperature and streamflow data were available for each location and may not have captured the full range of possible conditions. Seasonal variation in the amount of snowpack and timing of spring melt may affect the timing and temperature of surface flow inputs. For example, among years (2018–2021) snowpack differed at the end of April by 26–60 cm at snow measuring stations at the headwaters of the Nicola River, Clapperton Creek, and Coldwater River. As more years of streamflow and stream temperature data are measured, the magnitude and timing of spring freshet could be incorporated into predicting the influence of streamflow on stream temperature and thermal sensitivity of streams. Finally, models predicting stream temperature are correlative and do not represent the complex causal relationships among air temperature, streamflow, and water temperature. Therefore, our models do not explicitly account for numerous processes (e.g., groundwater exchange) that influence water temperature dynamics (Johnson, 2003; Webb & Nobilis, 1997).

The variable influence of streamflow on stream temperature highlights potential challenges and opportunities for managing aquatic habitat in the Nicola River basin. High air temperatures and low flows in summer months create the potential for negative temperature impacts on imperiled salmon (Figure 2). Our results suggest that reservoir releases from Nicola Lake have limited leverage to mitigate high-temperature risk, at least within the current constraints of reservoir levels. For example, Nicola River upstream of Clapperton Creek is downstream of a small dam at the outlet of Nicola Lake and streamflow had a positive effect on thermal sensitivity, which is likely due to surface releases being warmer than baseflow at this site (Walthers & Nener, 1997; Zaidel et al., 2021). Nevertheless, reservoir releases are likely still important to maintain sufficient streamflow and connectivity for migrating and spawning Pacific salmon. Management actions at the watershed scale may be more effective for managing stream temperatures in the Nicola River basin. For example, riparian restoration can result in cooler daily maximum stream temperatures even under future climate warming scenarios (e.g., Wondzell et al., 2019). Forest management can also help reduce earlier advancement of the spring freshet, maintaining cooler snowmelt inputs into streams during summer months (Gronsdahl et al., 2019; Perry & Jones, 2017; Winkler et al., 2017). Groundwater discharge is another important source of cool water to streams and maintaining groundwater input in the Nicola River basin could increase baseflow and decrease stream temperature. Removal of upland vegetation decreases infiltration of groundwater on hillslopes and pumping wells for irrigation and municipal water sources can decrease groundwater discharge into streams (Hester & Doye, 2011; Poole & Berman, 2001). In addition, water withdrawals for irrigation can result in warmer stream temperatures by reducing groundwater discharge compared with stream temperatures during stream diversion for irrigation or natural conditions (Essaid & Caldwell, 2017). Limiting land use and groundwater withdrawals can help maintain cold-water refugia (Kurylyk et al., 2015) and other actions, such as introducing beaver dam analogs, can introduce thermal heterogeneity to fish habitat (Dzara et al., 2019).

Changes to streamflow and temperature can have negative consequences for fishes and other aquatic organisms. Therefore, implementing environmental flows and improving water quality are important actions toward reducing the loss of freshwater biodiversity (Tickner et al., 2020). Assessing the cumulative effects of local stressors on streamflow and temperature is urgently needed to identify actions to mitigate or offset the consequences of oncoming climate change (Moore & Schindler, 2022). Further, understanding the benefits and limitations of different management levers allows for resources to be effectively used to promote resilient aquatic ecosystems.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Marta E. Ulaski https://orcid.org/0000-0002-7604-3475

REFERENCES

Albers, S. J. (2017). Tidyhydat: Extract and tidy Canadian hydrometric data. *Journal of Open Source Software*, *2*, 511.

Arnold, T. W. (2010). Uninformative parameters and model selection using Akaike's information criterion. *Journal of Wildlife Management*, *74*, 1175–1178.

Beaufort, A., Moatar, F., Sauquet, E., Loicq, P., & Hannah, D. M. (2020). Influence of landscape and hydrological factors on stream-air temperature relationships at regional scale. *Hydrological Processes*, *34*, 583–597.

Bennett, J. M., Calosi, P., Cusela-Trullas, S., Martínez, B., Sunday, J., Algar, A. C., Araújo, M. B., Hawkins, B. A., Keith, S., Kühn, I., Rahbek, C., Rodríguez, L., Singer, A., Villalobos, F., Olalla-Tárraga, M. A., & Morales-Castilla, I. (2018). GlobTherm, a global database on thermal tolerances for aquatic and terrestrial organisms. *Scientific Data*, *5*, 1–7.

Binkley, D., & Brown, T. C. (1993). Forest practices as nonpoint sources of pollution in North America. *JAWRA Journal of the American Water Resources Association*, *29*, 729–740.

Brockwell, P. J., & Davis, R. A. (2002). *Introduction to time-series and forecasting*. Springer.

Brown, G. W. (1969). Predicting temperatures of small streams. *Water Resources Research*, *5*, 68–75.

Burnham, K. P., & Anderson, D. R. (2002). Model selection and multimodel inference: a practical information-theoretic approach. In *Ecological Modelling*, (2nd ed.). Springer.

Chezik, K. A., Anderson, S. C., & Moore, J. W. (2017). River networks dampen long-term hydrological signals of climate change. *Geophysical Research Letters*, *44*, 725–7264.

Cline, T. J., Schindler, D. E., Walsworth, T. E., French, D. W., & Lisi, P. J. (2020). Low snowpack reduces thermal response diversity among streams across a landscape. *Limnology and Oceanography Letters*, *5*, 254–263.

COSEWIC. (2020). *COSEWIC assessment and status report on the Chinook Salmon Oncorhynchus tshawytscha, Designatable units in southern British Columbia (part two–Designatable units with high levels of artificial releases in the last 12 years), in Canada* (p. 203). *Committee on the Status of Endangered Wildlife in Canada*.

Dzara, J. R., Neilson, B. T., & Null, S. E. (2019). Quantifying thermal refugia connectivity by combining temperature modeling, distributed temperature sensing, and thermal infrared imagin. *Hydrology and Earth System Sciences*, *23*, 2965–2982.

Essaid, H. I., & Caldwell, R. R. (2017). Evaluating the impact of irrigation on surface water-groundwater interaction and stream temperature in an agricultural watershed. *Science of the Total Environment*, *599*, 581–596.

Gronsdahl, S., Moore, R. D., Rosenfeld, J., McCleary, R., & Winkler, R. (2019). Effects of forestry on summertime low flows and physical fish habitat in snowmelt-dominant headwater catchments of the Pacific northwest. *Hydrological Processes*, *33*, 3152–3168.

Hester, E. T., & Doye, M. W. (2011). Human impacts to river temperature and their effects on biological processes: A quantitative synthesis. *JAWRA Journal of the American Water Resources Association*, *47*, 571–587.

Hilderbrand, R. H., Kashiwagi, M. T., & Prochaska, A. P. (2014). Regional and local scale modeling of stream temperatures and spatio-temporal variation in thermal sensitivities. *Environmental Management*, *54*, 14–22.

Hostetler, S. W. (1991). Analysis and modeling of long-term stream temperatures on the Steamboat Creek basin, Oregon: Implications for land use and fish habitat. *Water Resources Bulletin*, *27*, 637–647.

Johnson, S. L. (2003). Stream temperature: Scaling of observations and issues for modelling. *Hydrological Processes*, *17*, 497–499.

Kaushal, S. S., Likens, G. E., Jaworski, N. A., Pace, M. L., Sides, A. M., Seekell, D., Belt, K. T., Secor, D. H., & Wingate, R. L. (2010). Rising stream and river temperatures in the United States. *Frontiers in Ecology and the Environment*, *8*, 461–466.

Kelleher, C., Wagener, T., Gooseff, M., McGlynn, B., McGuire, K., & Marshall, L. (2011). Investigating controls on thermal sensitivity of Pennsylvania streams. *Hydrological Processes*, *26*, 771–785.

Kurylyk, B. L., MacQuarrie, K. T. B., Linnansaari, T., Cunjak, R. A., & Curry, A. (2015). Preserving, augmenting, and creating cold-water thermal refugia in rivers: Concepts derived from research on the Miramichi River, New Brunswick (Canada). *Ecohydrology*, *8*, 1095–1108.

Lisi, P. J., Schindler, D. E., Cline, T. J., Scheuerell, M. K., & Walsh, P. B. (2015). Watershed geomorphology and snowmelt control stream thermal sensitivity to air temperature. *Geophysical Research Letters*, *42*, 3380–3388.

Martins, E. G., Hinch, S. G., Patterson, D. A., Hague, M. J., Cooke, S. J., Miller, K. M., Lapointe, M. F., English, K. K., & Farell, A. P. (2011). Effects of river temperature and climate warming on stock-specific survival of adult migrating Fraser River sockeye salmon (*Oncorhynchus nerka*). *Global Change Biology*, *17*, 99–114.

Mauger, S., Shaftel, R., Leppi, J. C., & Rinella, D. J. (2017). Summer temperature regimes in southcentral Alaska streams: Watershed drivers of variation and potential implications for Pacific salmon. *Canadian Journal of Fisheries and Aquatic Sciences*, *74*, 702–715.

Mayer, T. D. (2012). Controls of summer stream temperature in the Pacific northwest. *Journal of Hydrology*, *475*, 323–335.

Mohseni, O., & Stefan, H. G. (1999). Stream temperature/air temperature relationship: A physical interpretation. *Journal of Hydrology*, *218*, 128–141.

Moore, J. W., & Schindler, D. E. (2022). Getting ahead of climate change for ecological adaptation and resilience. *Science*, *376*, 1421–1426.

Moore, R. D., Spittlehouse, D. L., & Story, A. (2005). Riparian microclimate and stream temperature response to forest harvesting: A review. *Journal of the American Water Resources Association*, *41*, 813–834.

Nelitz, M. A., Macisaac, E. A., & Peterman, R. M. (2007). A science-based approach for identifying temperature-sensitive streams for rainbow trout. *North American Journal of Fisheries Management*, *27*, 405–424.

Niedrist, G. H., & Füreder, L. (2020). Real-time warming of alpine streams: (re)defining invertebrates' temperature preferences. *River Research and Applications*, *37*, 283–293.

Olden, J. D., & Naiman, R. J. (2010). Incorporating thermal regimes into environmental flows assessments: Modifying dam operations to restore freshwater ecosystem integrity. *Freshwater Biology*, *55*, 86–107.

Overland, J. E. (2021). Causes of the record-breaking Pacific northwest heatwave, late June 2021. *Atmosphere*, *12*, 1434.

Perry, T. D., & Jones, J. A. (2017). Summer streamflow deficits from regenerating Douglas-fir forest in the Pacific northwest, USA. *Ecohydrology*, *10*, e1790.

Poole, G. C., & Berman, C. H. (2001). An ecological perspective on in-stream temperature: Natural heat dynamics and mechanisms of human-cause thermal degradation. *Environmental Management*, *27*, 787–802.

R Development Core Team. (2018). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing.

Richter, A., & Kolmes, S. A. (2005). Maximum temperature limits for Chinook, coho, and chum salmon and steelhead trout in the Pacific northwest. *Reviews in Fisheries Science*, *13*, 23–49.

Rood, K. M., & Hamilton, R. E. (1995). *Hydrology and water use for salmon streams in the Thompson River watershed, British Columbia*. Department of Fisheries and Oceans Canada.

Schielzeth, H. (2010). Simple means to improve the interpretability of regression coefficients. *Methods in Ecology and Evolution*, *1*, 103–113.

Sinokrot, B. A., & Gulliver, J. S. (2000). In-stream flow impact on river water temperatures. *Journal of Hydraulic Research*, *38*, 339–349.

Sinokrot, B. A., Stefan, H. G., McCormick, J. H., & Eaton, J. G. (1995). Modeling of climate change effects on stream temperatures and fish habitats below dams and near groundwater inputs. *Climatic Change*, *30*, 181–200.

Smith, K., & Lavis, M. E. (1975). Environmental influences on temperature of a small upland stream. *Oikos*, *26*, 228–236.

Sohrabi, M. M., Benjankar, R., Tonina, D., Wenger, S. J., & Isaak, D. J. (2017). Estimation of daily stream water temperatures with a Bayesian regression approach. *Hydrological Processes*, *31*, 1719–1733.

Tague, C., Farrell, M., Grant, G., Lewis, S., & Rey, S. (2007). Hydrogeologic controls on summer stream temperatures in the McKenzie River basin, Oregon. *Hydrological Processes*, *21*, 3288–3300.

Tickner, D., Opperman, J. J., Abel, R., Acreman, M., Arthington, A. H., Bunn, S. E., Cooke, S. J., Dalton, J., Darwall, W., Edwards, G., Harrison, I., Hughes, K., Jones, T., Leclère, D., Lynch, A. J., Leonard, P., McClain, M. E., Muruven, D., Olden, J. D., … Young, L. (2020). Bending the curve of global freshwater biodiversity loss: An emergency recovery plan. *Bioscience*, *70*, 330–342.

Walthers, L. C., & Nener, J. C. (1997). "Continuous water temperature monitoring in the Nicola River, B.C., 1994: Implications of high measured temperatures for anadromous salmonids.". Canadian Technical Report of Fisheries and Aquatic Sciences. 1997.

Warkentin, L. (2020). *Regimes of river temperature and flow in an interior watershed, and their implications for Chinook salmon*. Master's thesis. Simon Fraser University.

Warkentin, L. (2022). Low summer river flows associated with low productivity of Chinook salmon in a watershed with shifting hydrology. *Ecological Solutions and Evidence*, *3*, e12124.

Webb, B. W., & Nobilis, F. (1997). Long-term perspective on the nature of the air-water temperature relationship: A case study. *Hydrological Processes*, *11*, 137–147.

Webb, B. W., & Walling, D. E. (1997). Complex summer water temperature behavior below a UK regulating reservoir. *Regulated Rivers: Research & Management*, *13*, 463–477.

Webb, B. W., & Zahng, Y. (1997). Spatial and seasonal variability in the components of the river heat budget. *Hydrological Processes*, *11*, 79–101.

Webb, B. W., Hannah, D. M., Moore, R. D., Brown, L. E., & Nobilis, F. (1996). Recent advances in stream and river temperature research. *Hydrological Processes*, *22*, 902–918.

Wenger, S. J., Isaak, D. J., Luce, C. H., Nevillle, H. M., Fausch, K. D., Dunham, J. B., Dauwalter, D. C., Young, M. K., Elsner, M. M., Rieman, B. E., Hamlet, A. F., & Williams, J. E. (2011). Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. *Proceedings of the National Academy of Sciences*, *108*, 14175–14180.

Wild, M., Grieser, J., & Schär, C. (2008). Combined surface solar brightening and increasing greenhouse effect support intensification of the global land-based hydrological cycle. *Geophysical Research Letters*, *35*, L07711.

Winkler, R., Spittlehouse, D., & Boon, S. (2017). Streamflow response to clear-cut logging on British Columbia's Okanagan plateau. *Ecohydrology*, *10*, e1836.

Wondzell, S. M., Diabat, M., & Haggerty, R. (2019). What matters most: Are future stream temperatures more sensitive to changing air temperatures, discharge, or riparian vegetation? *JAWRA Journal of the American Water Resources Association*, *55*, 116–132.

Zaidel, P. A., Roy, A. H., Houlle, K. M., Lambert, B., Letcher, B. H., Nislow, K. H., & Smith, C. (2021). Impacts of small dams on stream temperature. *Ecological Indicators*, *49*, 1456–1472.

SUPPORTING INFORMATION

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