Stream Temperatures in the Forks and Main Stem of the White River in Northwest Colorado (2019-2020)

Brian W. Hodge
Trout Unlimited

Tory Eyre
Colorado Parks and Wildlife

February 2021

Abstract

The upper White River in northwest Colorado supports an important coldwater fishery and is the focus of ongoing studies of benthic macroinvertebrates and nuisance algal blooms. Despite the presumed importance of stream temperature to aquatic organisms, relatively little is known about the spatio-temporal patterns of stream temperature in the upper White River. From April of 2019 to September of 2020 we monitored stream temperature across a 64-mile extent of the North Fork, South Fork, and main stem of the White River. Specifically, we deployed pairs of data-logging temperature sensors at 20 sites, all of which aligned with locations at which the U.S. Geological Survey (USGS) is monitoring algae and other water quality parameters. The objectives of our study were to i) identify spatial and temporal trends in stream temperature, ii) explore local effects of air temperature and discharge on stream temperature, iii) examine the thermal suitability of the upper White River for aquatic biota, and iv) provide the USGS with continuous temperature data for inclusion in their investigation of benthic algal occurrence. In 2019-2020, stream temperature varied among sites and seasons, with hourly minima and maxima ranging from -0.10°C to 22.78°C, respectively. Temperature generally increased with distance downstream (0.06-0.09°C/mile), and summer of 2020 was 1.37°C warmer than summer of 2019. When a site-specific regression model was fitted, discharge and 3-day mean air temperature explained 95% of the variability in stream temperature. Fish-temperature metrics, the 30-day mean and 7-day mean maximum, revealed that the White River above Meeker was suitable for coldwater fishes in both 2019 and 2020. Degree-days, a common index for potential growth and development, accumulated significantly faster at downstream than upstream locations. Continual year-round temperature monitoring would be an easy and relatively inexpensive way to track long-term changes, or lack thereof, in the upper White River.

CONVERSION FACTORS

°C	°F
0	32
5	41
10	50
15	59
20	68
25	77
30	86

$$°F = \left(°C \times \frac{9}{5}\right) + 32$$

$$°C = (°F - 32) \times \frac{5}{9}$$

INTRODUCTION

Temperature is a critical driving factor in the biology of organisms. For example, in aquatic environments, water temperature influences the distribution and abundance of species, including benthic macroinvertebrates (Lessard and Hayes 2002; Jacobsen and Marín 2008), algae (Kumar et al. 2009; Singh and Singh 2015), and fish (Roberts et al. 2013; Dobos et al. 2016; Hodge et al. 2017). Moreover, water temperature can have both direct and indirect effects on aquatic organisms—for example, by influencing their metabolism (Mayfield and Cech 2004) and the condition (e.g., dissolved oxygen concentration) of their environments (Schmitz 1996; Bjornn and Reiser 1991).

As cold-blooded animals, fish are particularly sensitive to the thermal regime of their environment. Moreover, water temperature influences their distribution and movement (Dunham et al. 2003; Petty et al. 2012; Hodge et al. 2017), growth and development (Bear et al. 2007; Coleman and Fausch 2007), and survival or mortality (Underwood et al. 2012; Brinkman et al. 2013; Ziegler et al. 2013). Because of the overall importance of thermal regimes to fish and ease with which temperature data can be collected, temperature monitoring is a common means for tracking and predicting fish habitat suitability over time and space (e.g., Rahel et al. 1996; Wenger et al. 2011; Roberts et al. 2013).

From its headwaters down to the town of Meeker, Colorado, the White River is a coldwater fishery with an assemblage that includes species of conservation and recreational value. Important native species in this reach include Colorado River Cutthroat Trout *Oncorhynchus clarkii pleuriticus*, Mountain Whitefish *Propsopium williamsoni*, and Mottled Sculpin *Cottus bairdi*, among others. Sportfish in the reach include Rainbow Trout *O. mykiss*, Brown Trout *Salmo trutta*, and Brook Trout *Salvelinus fontinalis*.

Benthic algae blooms began to occur in the White River around 2012 (B. Hodge, personal observation), for reasons unknown and with ecological effects unknown. A preliminary study by Colorado Parks and Wildlife (CPW) identified *Cladophora glomerata* as a key alga of concern and nitrogen as a key limiting factor to algal growth, and, further, recommended that greater effort be placed on monitoring algal biomass (CPW 2017). In 2017 a local stakeholder group contracted with the U.S. Geological Survey (USGS) to investigate driving factors behind the algal blooms. Although research suggests that water temperature can influence the distribution and growth of algae (e.g., Whitton 1970; Kumar et al. 2009; Singh and Singh 2015; but see

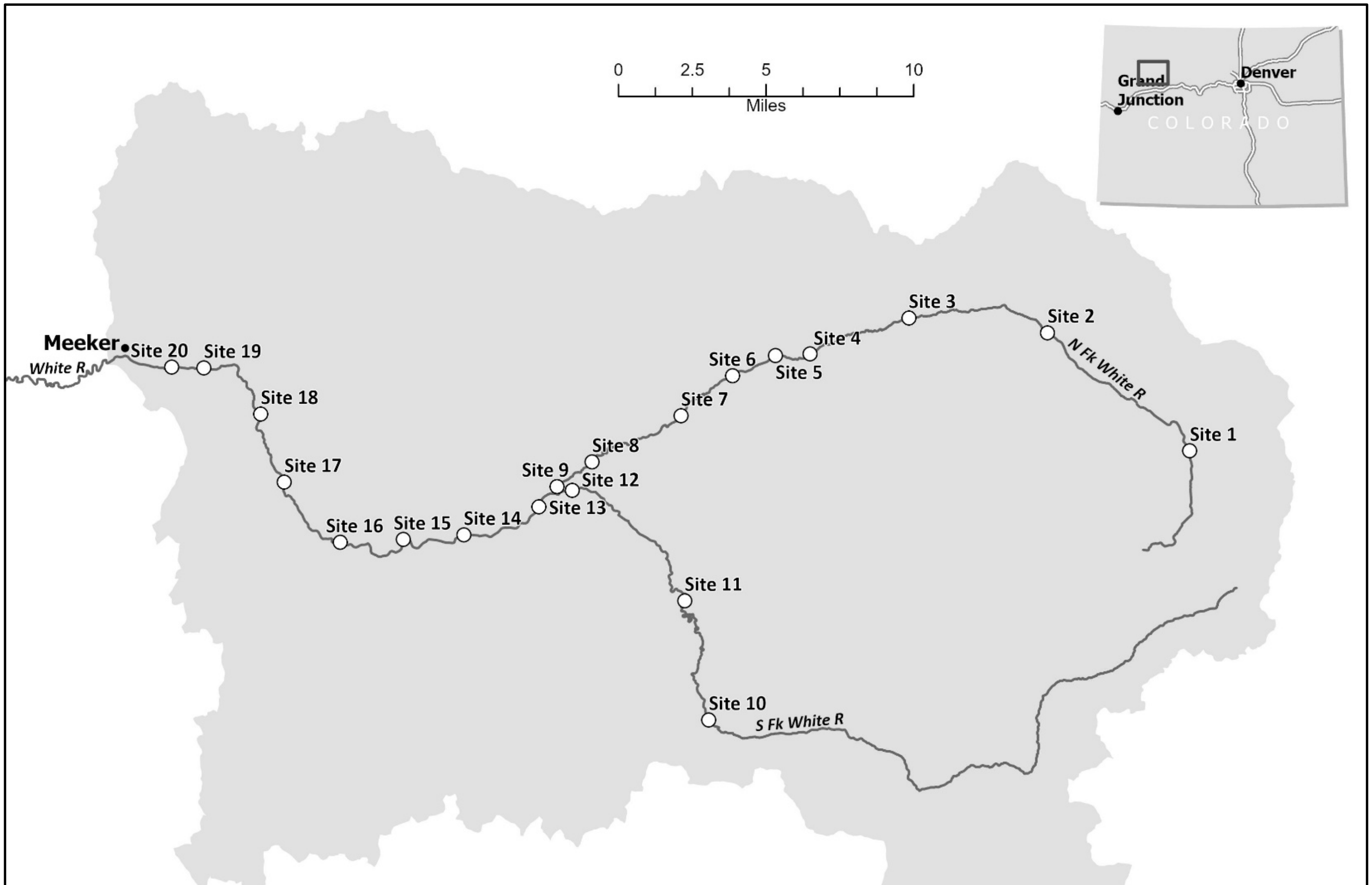
Anderson 2000), resource limitations precluded continuous temperature monitoring from being included in the USGS scope of work. Meanwhile, Trout Unlimited and CPW were leading a local study on benthic macroinvertebrates that might benefit from the insight of temperature data.

The objectives of our study were to i) identify spatial and temporal trends in water temperature in the North Fork, South Fork, and main stem of the White River; ii) explore local effects of air temperature and discharge on stream temperature; iii) examine the thermal suitability of the upper White River for aquatic biota; and iv) provide to the USGS a source of continuous temperature data for inclusion in their investigation of benthic algal occurrence.

METHODS

Study area.—The White River flows for approximately 225 miles from its headwaters in Colorado to its confluence with the Green River in Utah. By design, our study area overlapped exactly with that of the USGS study (Figure 1). Specifically, we focused on the North Fork from just below Trappers Lake to the confluence with the South Fork (29 river miles), the South Fork from just below the Flat Tops Wilderness boundary to the confluence with the North Fork (14 river miles), and the main stem from the confluence of the Forks to just above the town of Meeker, Colorado (20 river miles). Individual temperature monitoring sites were selected to coincide with USGS study sites (n = 20).

Data collection.—Stream temperature was monitored from April of 2019 to September of 2020 at 15 of 20 sites, and from August of 2019 to September of 2020 at five of 20 sites. Two data-logging temperature sensors, or temperature loggers (TidbiT v2; Onset Corporation, Bourne, MA), were deployed at each site: each one at a different location but both in locations where readings would be representative of the water column. Each temperature logger was placed in a metal housing and anchored to the streambed with a rebar pin, and each recorded temperature (± 0.21°C) every hour on the hour between times of deployment and retrieval. Prior to deployment and subsequent to retrieval, all temperature loggers were subjected to and passed “ice bucket” tests of accuracy and precision (i.e., all means were within 0.21°C of 0.00°C; Dunham et al. 2005).



Site #	Description	Site #	Description	Site #	Description	Site #	Description
1	North Fork below Trappers Lake	6	North Fork above Fawn Creek	11	South Fork at CR10	16	Main stem above Miller Creek
2	North Fork below Mirror Creek	7	North Fork at CR14	12	South Fork at Bel Aire S.W.A	17	Main stem above Highland Ditch
3	North Fork below Missouri Creek	8	North Fork at Buford	13	Main stem below Big Beaver Creek	18	Main stem above Coal Creek
4	North Fork below Lost Creek	9	North Fork at Bel Aire S.W.A	14	Main stem below North Elk Creek	19	Main stem below Coal Creek
5	North Fork below Marvine Creek	10	South Fork at USFS Campground	15	Main stem above Dry Creek	20	Main stem above Meeker

Figure 1. Temperature monitoring sites on the North Fork, South Fork, and main stem of the White River, Colorado.

Data analyses.—Hourly temperature data were summarized into a number of different temperature statistics. When only one temperature logger was retrieved from a site (n = 4), all statistics were calculated from the single dataset. When both loggers were retrieved from a site (n = 16), the two hourly datasets were compared using a paired t-test. A site average was calculated for each hourly reading in the event readings from paired loggers did not differ (12 of 16). However, if the mean difference between paired loggers was significant (4 of 16), hourly data from both loggers were carefully examined and compared to data from adjacent monitoring sites. We ultimately omitted one dataset from each of the four logger pairs based on evidence of temperature attenuation. For example, data suggested that three of four loggers were temporarily covered by sediment and thus failed to accurately track temperature. Daily metrics were calculated from hourly data, and monthly, summer (June 20-September 21), and annual (September 1-August 31) statistics were calculated from daily metrics. All calculations were performed in R (R Core Team 2020).

We fit a number of models to test for patterns in stream temperature. Linear regression was used to test for relationships between temperature metrics and distance downstream, paired t-tests to test for differences between years, and analysis of variance to test for differences between forks. All statistical analyses were performed in R at $\alpha = 0.05$.

To explore the local relationship between air temperature, discharge, and stream temperature, we focused an analysis around the site above Coal Creek and the time period of April 2019-September 2020. Namely, we constructed a number of multiple regression models in which the response variable was mean daily stream temperature in the White River above Coal Creek. We hypothesized that stream temperature on any given day i could be a function of not only current air temperature but also of air temperature in the preceding days. Thus, we included seven predictor variables each for mean and maximum air temperature at Meeker: means for days i through i – 6 (i.e., up to a seven-day average preceding and including day i), and mean maxima for days i through i - 6. Mean daily discharge (cfs) at the White River above Coal Creek was included as a covariate. All climate data were derived from the National Centers for Environmental Information (Station = USW00094050; NOAA 2020) and all discharge data from the National Water Information System (Gage = 09304200; USGS 2020). Candidate models were constructed to include air temperature, discharge, and the interaction of the two, but were constrained to include no more than one air temperature metric. The plausibility of, and support for, each candidate model was evaluated using Akaike's Information Criterion (AIC; Akaike 1974; Burnham and Anderson 2002) and the MuMIn package (Bartón 2020) for R. Additionally, Akaike weights (w_i) were calculated to assess the probability that the best-supported models were selected. Model averaging with shrinkage (Lukacs et al. 2010) was used to derive parameter estimates and error terms from more than one plausible model (ΔAIC < 4).

A number of temperature metrics were calculated in consideration of aquatic biota. Because Colorado River Cutthroat trout (CRCT) are native to the White River and their upper thermal tolerance is similar to that of the other salmonids in the basin (Brinkman et al. 2013), we used metrics specific to CRCT to gauge habitat suitability for coldwater species in general. The 30-day average temperature was calculated for each site to evaluate the potential for fish production; growth and recruitment of CRCT are optimized when the maximum 30-day average (M30AT) is 9.0-18.0°C (Roberts et al. 2013). The weekly mean maximum temperature was calculated for each site as a prediction of fish population persistence; survival of CRCT is expected to occur when the warmest weekly mean maximum (MWMT) is ≤ 26.0°C (Roberts et al. 2013). For each site we also calculated degree-days (a running cumulative sum of mean daily temperatures), which can serve as a proxy for growth of aquatic organisms, including fish and algae (Coleman and Fausch 2007; Ralston et al. 2014; Wittman et al. 2017). Degree-day accumulations were calculated from an arbitrary but consistent starting point of January 1, 2020 (Ralston et al. 2014).

RESULTS

Spatial and Temporal Patterns in Temperature

Stream temperature varied among sites and seasons (Figure 2; Table 1). Overall, hourly stream temperature ranged from an absolute minimum of -0.10°C in December of 2019 to an absolute maximum of 22.78°C in August of 2020. Mean daily temperatures ranged from 0.00 to 18.98°C, mean summer (June 20-September 21) temperatures from 10.02 to 15.87°C, and mean annual (September 1-August 31) temperatures from 4.80 to 7.77°C.

Stream temperature varied by river mile but not between forks of the White River. Mean summer stream temperature generally increased with distance downstream (2020; $P < 0.001$, $R^2 = 0.616$ [0.983 excluding Site 1]), as did mean annual stream temperature ($P < 0.001$, $R^2 = 0.714$ [0.937 excluding Site 1]). Average rates of warming were 0.10°C/mile and 0.09°C/mile in summers of 2019 and 2020 (but see site representation), and 0.06°C/mile across a year (Table 2).

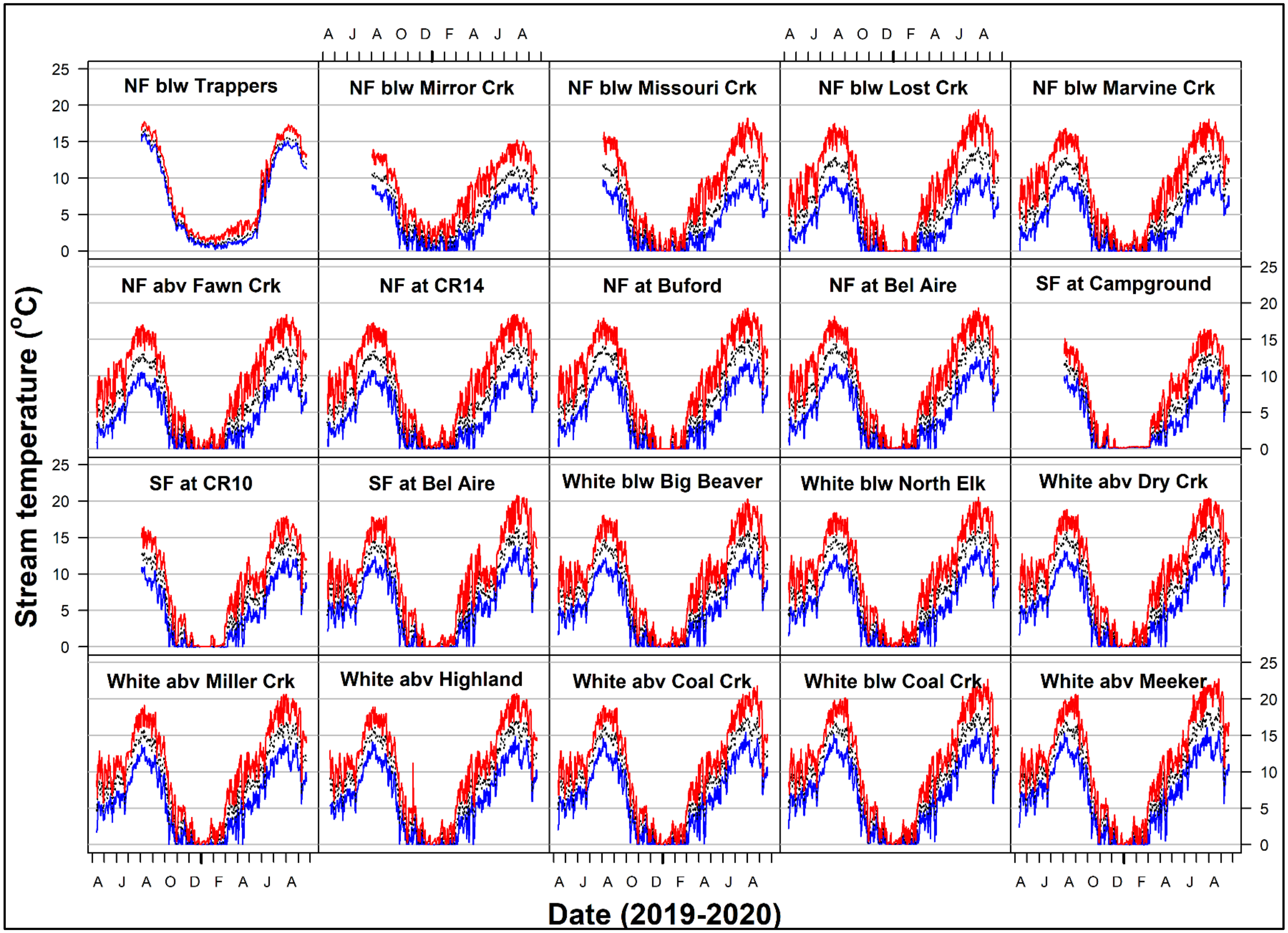


Figure 2. Maximum (red), mean (black), and minimum (blue) daily stream temperature at 20 sites on the North Fork, South Fork, and main stem of the White River in 2019-2020.

Table 1. Mean summer (June 20-September 21) stream temperature in the North Fork, South Fork, and main stem of the White River.

	Mean stream temperature (°C; ± 95% confidence limits)							
	June		July		August		Summer	
Location	2019	2020	2019	2020	2019	2020	2019	2020
North Fork								
blw. Trappers Lake		10.30 ± 0.59		14.49 ± 0.26	15.76 ± 0.27	15.25 ± 0.09		14.05 ± 0.29
blw. Mirror Creek		9.00 ± 0.27		10.52 ± 0.16	10.07 ± 0.14	10.66 ± 0.21		10.02 ± 0.22
blw. Missouri Creek		9.55 ± 0.42		11.77 ± 0.22	11.09 ± 0.20	11.87 ± 0.26		11.08 ± 0.29
blw Lost Creek	7.30 ± 0.38	10.24 ± 0.47	11.24 ± 0.29	12.77 ± 0.26	11.96 ± 0.22	12.85 ± 0.29	10.85 ± 0.34	11.96 ± 0.33
blw Marvine Creek	7.62 ± 0.38	10.21 ± 0.44	11.19 ± 0.28	12.36 ± 0.23	11.86 ± 0.22	12.46 ± 0.28	10.80 ± 0.33	11.64 ± 0.30
abv Fawn Creek	7.77 ± 0.37	10.42 ± 0.46	11.37 ± 0.31	12.72 ± 0.24	12.13 ± 0.23	12.82 ± 0.29	11.01 ± 0.34	11.96 ± 0.32
at CR14	7.97 ± 0.39	10.72 ± 0.47	11.70 ± 0.32	13.06 ± 0.25	12.48 ± 0.25	13.11 ± 0.29	11.31 ± 0.35	12.25 ± 0.33
at Buford	8.32 ± 0.41	11.24 ± 0.51	12.15 ± 0.35	13.79 ± 0.27	13.07 ± 0.26	13.88 ± 0.32	11.80 ± 0.37	12.94 ± 0.36
at Bel Aire	8.54 ± 0.41	11.46 ± 0.51	12.38 ± 0.36	14.01 ± 0.27	13.33 ± 0.26	14.13 ± 0.33	12.03 ± 0.37	13.16 ± 0.36
South Fork								
at Campground		8.63 ± 0.63		11.91 ± 0.26	10.93 ± 0.26	11.94 ± 0.27		11.04 ± 0.33
at CR10		9.45 ± 0.71		13.16 ± 0.28	12.03 ± 0.25	13.42 ± 0.33		12.39 ± 0.36
at Bel Aire	7.38 ± 0.40	10.43 ± 0.73	11.34 ± 0.62	14.44 ± 0.30	13.54 ± 0.26	14.72 ± 0.36	11.72 ± 0.46	13.57 ± 0.40
Main Stem								
blw Big Beaver Creek	7.67 ± 0.39	10.84 ± 0.71	11.66 ± 0.58	14.29 ± 0.27	13.54 ± 0.26	14.44 ± 0.34	11.83 ± 0.44	13.42 ± 0.38
blw North Elk Creek	8.55 ± 0.39	11.55 ± 0.64	12.42 ± 0.51	14.74 ± 0.29	14.06 ± 0.27	14.72 ± 0.35	12.43 ± 0.42	13.82 ± 0.38
abv Dry Creek	8.67 ± 0.40	11.82 ± 0.67	12.64 ± 0.53	15.15 ± 0.30	14.36 ± 0.27	15.12 ± 0.36	12.68 ± 0.44	14.19 ± 0.39
abv Miller Creek	8.85 ± 0.41	12.05 ± 0.68	12.85 ± 0.54	15.36 ± 0.30	14.56 ± 0.28	15.34 ± 0.36	12.88 ± 0.44	14.40 ± 0.39
abv. Highland Ditch	9.08 ± 0.41	12.32 ± 0.68	13.11 ± 0.55	15.64 ± 0.30	14.78 ± 0.29	15.58 ± 0.36	13.11 ± 0.44	14.65 ± 0.39
abv Coal Creek	9.31 ± 0.41	12.61 ± 0.68	13.35 ± 0.56	15.90 ± 0.31	15.07 ± 0.29	15.93 ± 0.33	13.38 ± 0.45	14.94 ± 0.39
blw Coal Creek	10.01 ± 0.41	13.54 ± 0.69	13.82 ± 0.54	16.48 ± 0.31	15.71 ± 0.26	16.79 ± 0.33	13.97 ± 0.45	15.66 ± 0.41
abv Meeker	9.93 ± 0.42	13.56 ± 0.70	13.91 ± 0.56	16.68 ± 0.32	15.88 ± 0.26	17.06 ± 0.33	14.08 ± 0.47	15.87 ± 0.42
All								
ALL	8.46 ± 0.48	11.00 ± 0.65	12.34 ± 0.51	13.96 ± 0.78	13.31 ± 0.80	14.10 ± 0.67	12.26 ± 0.59	13.15 ± 0.75

Note: Because loggers we not deployed at the upstream-most locations (Sites 1-3 and 10-11) until August 2, 2019, neither early-summer nor overall-summer means could not be calculated for those sites.

Three exceptions to the rule of downstream warming were observed in the North Fork. For example, in the reach below Trappers Lake, water was significantly cooler exiting the reach (at Site 2) than entering it (at Site 1), both during summer and across seasons. A similar summer pattern was observed in the reach that includes the confluence with Marvine Creek. When roughly equal lengths of the North Fork and South Fork were compared, 11.7 and 13.5 miles, respectively, mean summer stream temperature did not differ (12.32 ± 0.63 °C [mean ± 95% confidence limits] vs. 12.33 ± 3.14°C ; $F_{1,7} < 0.001$, $P = 0.981$). The same was true of mean annual stream temperature (5.82 ± 0.34°C vs. 5.57 ± 1.88°C; $F_{1,7} = 0.496$, $P = 0.504$).

Table 2. Comparison of thermal gains (+) and losses (-) in reaches of the White River. *Summer* was defined as the period from June 20 through September 21, and *Year* by the period from September 1, 2019 through August 31, 2020.

		(Δ°C/mile; ± 95% confidence limits)		
		Summer		
Bottom of reach	Reach length (miles)	2019	2020	Year
		North Fork		
below Trappers Lake				
below Mirror Creek	7.9		-0.51 ± 0.03	-0.10 ± 0.03
below Missouri Creek	5.6		0.19 ± 0.01	-0.03 ± 0.02
below Lost Creek	4.4		0.20 ± 0.01	0.03 ± 0.01
below Marvine Creek	1.5	-0.03 ± 0.02	-0.21 ± 0.02	0.08 ± 0.02
above Fawn Creek	1.8	0.12 ± 0.01	0.18 ± 0.01	0.06 ± 0.01
at CR14	2.5	0.12 ± 0.01	0.12 ± 0.01	0.08 ± 0.00
at Buford	4.1	0.12 ± 0.01	0.17 ± 0.01	0.06 ± 0.01
at Bel Aire S.W.A.	1.6	0.15 ± 0.00	0.14 ± 0.01	0.11 ± 0.01
		South Fork		
at USFS Campground				
at CR10	6.8		0.20 ± 0.01	0.12 ± 0.01
at Bel Aire S.W.A.	6.7		0.18 ± 0.01	0.11 ± 0.01
		Main stem		
below Big Beaver Creek				
below North Elk Creek	3.1	0.20 ± 0.01	0.13 ± 0.01	0.10 ± 0.01
above Dry Creek	2.5	0.10 ± 0.01	0.15 ± 0.01	0.07 ±0.01
above Miller Creek	2.8	0.07 ± 0.00	0.07 ± 0.00	0.05 ± 0.00
above Highland Ditch	3.4	0.07 ± 0.00	0.08 ± 0.00	0.06 ± 0.00
above Coal Creek	2.7	0.10 ± 0.00	0.11 ± 0.01	0.06 ± 0.01
below Coal Creek	3.7	0.16 ± 0.01	0.20 ± 0.02	0.11 ± 0.01
above Meeker	1.4	0.07 ± 0.01	0.14 ± 0.01	0.04 ± 0.01
		All		
All		0.10 ± 0.04	0.09 ± 0.09	0.06 ± 0.03

Stream temperatures were significantly warmer during summer of 2020 than during summer of 2019, though the difference varied across the season (Table 1). In 2020, mean June, July, and August temperatures were 3.07, 2.15, and 0.79°C higher than in the same months of the prior year ($t \geq 9.520$, df = 14-19, $P < 0.001$). The overall summer (June 20-September 21) mean was 1.37°C higher in 2020 than 2019 ($t = -16.29$, df = 14, $P < 0.001$).

Predictors of Stream Temperature

Model selection revealed two plausible candidates for predicting stream temperature in the White River above Coal Creek ($\Delta AIC < 4$; Table 3). Discharge and air temperature were significant predictors in both models ($P \leq 0.002$), which differed only in inclusion of the interaction term. Model-averaged parameter estimates showed that stream temperature above Coal Creek was best estimated by the equation:

$$T_W = 4.37600 - 0.00115Q + 0.55510T_{A3} - 0.00001\,(Q^*\,T_{A3}); \quad (1)$$

where mean daily water temperature on day i (T_W) is a function of mean daily discharge on day i (Q), mean air temperature on days i-2 through i (i.e., the 3-day mean; T_{A3}), and their interaction (Table 4). Together, discharge and air temperature accounted for approximately 95% of the variability in stream temperature in both plausible models ($R^2 = 0.949$).

Table 3. The top five candidate models for describing the relationship between stream temperature, discharge (Q), and air temperature (mean for days i through i - j; $T_{A\,i}$). Models were ranked according to Akaike's Information Criterion (AIC; ΔAIC = AIC difference; w_i = Akaike weight).

Model structure	AIC	ΔAIC	w_i
$Q + T_{A3} + (Q^*T_{A3})$	1724.1	0.00	0.510
$Q + T_{A3}$	1724.2	0.12	0.480
$Q + T_{A4}$	1733.3	9.19	0.005
$Q + T_{A4} + (Q^*T_{A4})$	1733.8	9.70	0.004
$Q + T_{A4} + (Q^*T_{A2})$	1763.3	39.17	0.000

Table 4. Model-averaged parameter estimates (*b*), standard errors (SE), and importance values for models predicting temperature as a function of discharge (Q) and 3-day mean air temperature (T_{A3}).

Variable	*b*	SE	Importance
Q	-0.001154	0.0003137	1.00
T_{A3}	0.5551	0.00821	1.00
Q^*T_{A3}	-0.00001429	0.00001966	0.51

Biological Temperature Metrics

Fish-temperature metrics varied among sites and between years (Table 5). M30ATs ranged from 10.82 to 17.25°C, and MWMTs from 14.66 to 21.75°C. Both the M30AT and MWMT tended to increase with distance downstream ($P < 0.001$, $R^2 \geq 0.617$), and paired t-tests showed that both metrics were higher in 2020 than 2019 (mean differences = 0.98 and 1.85°C, respectively; $t \geq 13.709$ df = 14, $P < 0.001$).

Table 5. Summary of fish-temperature metrics from the North Fork, South Fork, and main stem of the White River (M30AT = maximum 30-day average temperature, MWMT = maximum weekly mean maximum temperature). Optimal growth and recruitment of Colorado River Cutthroat Trout (CRCT) occur when the M30AT is 9.0-18.0°C; survival of CRCT is expected when the MWMT is ≤ 26.0°C.

	Temperature metric (°C)					
	2019		2020		Both (mean)	
Location	M30AT	MWMT	M30AT	MWMT	M30AT	MWMT
North Fork						
below Trappers Lake			15.32	16.97	15.32	16.97
below Mirror Creek			10.82	14.66	10.82	14.66
below Missouri Creek			12.13	17.11	12.13	17.11
below Lost Creek	12.16	16.47	13.15	18.03	12.66	17.25
below Marvine Creek	12.07	16.00	12.70	17.00	12.39	16.50
above Fawn Creek	12.34	16.16	13.07	17.48	12.71	16.82
at CR14	12.71	16.51	13.41	17.82	13.06	17.17
at Buford	13.29	16.85	14.16	18.24	13.73	17.55
at Bel Aire S.W.A.	13.55	16.96	14.39	18.42	13.97	17.69
South Fork						
at USFS Campground			12.28	15.52	12.28	15.52
at CR10			13.65	17.11	13.65	17.11
at Bel Aire S.W.A.	13.67	17.12	14.97	19.98	14.32	18.55
Main stem						
below Big Beaver Creek	13.69	17.08	14.71	19.14	14.20	18.11
below North Elk Creek	14.20	17.44	15.16	19.32	14.68	18.38
above Dry Creek	14.51	17.71	15.57	19.66	15.04	18.69
above Miller Creek	14.72	17.88	15.78	19.76	15.25	18.82
above Highland Ditch	14.97	17.95	16.05	19.89	15.51	18.92
above Coal Creek	15.26	18.15	16.32	20.86	15.79	19.51
below Coal Creek	15.81	19.14	16.97	21.33	16.39	20.24
above Meeker	15.97	19.53	17.25	21.75	16.61	20.64
All						
All	13.93	17.40	14.39	18.50	14.16	17.95

Similar to and because of mean steam temperature, growing degree-days varied among sites and increased loosely with distance downstream (Table 6). Whereas headwater sites accumulated approximately 600-650 degree-days by July 1, 2020, sites near the confluence of Forks and below the confluence of the main stem and Coal Creek accumulated approximately 900 and 1,150 degree-days by the same date (Figure 3). Spring and summer degree-day accumulations were similar between North Fork and South Fork sites at the Bel Aire State Wildlife Area (i.e., Sites 9 and 12), though January-March accrual occurred more slowly in the South Fork.

DISCUSSION

Our findings regarding spatial patterns in temperature both aligned with and differed from predictions. We expected to see a relationship between stream temperature and river mile, as others have predicted and observed thermal gains with watershed area and distance downstream (e.g., Null et al. 2009; Hodge et al. 2017; Kaylor et al. 2019). Although lakes and reservoirs are known to have a warming effect on stream temperature (Maheu et al. 2016; Isaak et al. 2017), we were surprised that mean summer stream temperatures were as much as 5.0-6.0°C warmer below Trappers Lake than at the nearest site downstream. This difference in temperatures suggests that significant volumes of cold water are introduced to the North Fork between sites below Trappers Lake and Mirror Creek. Potential contributors include Lynx Creek, Big Fish Creek, and Picket Pin Creek, among others (including groundwater). That summer temperatures were consistently cooler below than above Marvine Creek, and in a reach that includes no other major confluences, might suggest that Marvine Creek is a substantial source of cold water. Meanwhile, that winter temperatures were consistently warmer below than above below Marvine Creek suggests that the reach is influenced by groundwater inputs to Marvine Creek and/or the North Fork itself.

We were not surprised by the finding of warmer stream temperatures in 2020 than 2019. We expected the greater runoff of 2019, relative to the runoff of 2020, to result in cooler stream temperatures that year (peak discharge was in the 88th and 24th percentiles, respectively; USGS). Meanwhile, air temperatures were similar between 2019 and 2020 (NOAA 2020), as verified by a paired t-test. Ultimately, our results (Equation 1) suggest that stream temperature is a function of air temperature, discharge, and the interaction of the two.

Table 6. A comparison of accumulated degree days since January 1, 2020 (± 95% confidence limits).

	Mar 1	Apr 1	May 1	Jun 1	Jul 1	Aug 1	Sep 1
				North Fork			
below Trappers Lake	66 ± 8	116 ± 16	179 ± 25	302 ± 32	614 ± 39	1,066 ± 47	1,537 ± 56
below Mirror Creek	96 ± 21	204 ± 42	342 ± 69	556 ± 93	826 ± 113	1,154 ± 138	1,483 ± 163
below Missouri Creek	41 ± 11	140 ± 31	270 ± 58	458 ± 84	746 ± 111	1,113 ± 144	1,479 ± 179
below Lost Creek	15 ± 5	110 ± 24	237 ± 52	439 ± 83	748 ± 114	1,146 ± 150	1,542 ± 187
below Marvine Creek	30 ± 8	129 ± 26	264 ± 52	478 ± 83	785 ± 113	1,171 ± 145	1,555 ±177
above Fawn Creek	27 ± 8	128 ± 26	268 ± 52	487 ± 83	802 ± 113	1,198 ± 145	1,594 ±177
at CR14	34 ± 9	143 ± 28	292 ± 55	518 ± 85	841 ± 115	1,248 ± 147	1,653 ± 178
at Buford	22 ± 7	137 ± 27	297 ± 54	536 ± 84	874 ± 114	1,304 ± 144	1,732 ± 173
at Bel Aire S.W.A.	27 ± 8	148 ± 28	315 ± 55	560 ± 84	905 ± 113	1,342 ± 142	1,778 ± 170
				South Fork			
at USFS Campground	14 ± 1	78 ± 11	207 ± 29	389 ± 54	650 ± 77	1,022 ± 100	1,391 ± 125
at CR10	7 ± 3	107 ± 22	279 ± 47	486 ± 69	773 ± 89	1,184 ± 115	1,598 ±138
at Bel Aire S.W.A.	11 ± 5	136 ± 27	338 ± 52	578 ± 71	894 ± 90	1,345 ± 117	1,799 ± 149
				Main stem			
below Big Beaver Creek	20 ± 8	146 ± 29	334 ± 55	576 ± 76	904 ± 99	1,350 ± 126	1,795 ± 157
below North Elk Creek	28 ± 11	161 ± 33	356 ± 59	617 ± 82	966 ± 106	1,426 ± 133	1,880 ± 161
above Dry Creek	27 ± 11	165 ± 34	369 ± 59	636 ± 82	993 ± 106	1,466 ± 133	1,932 ± 163
above Miller Creek	32 ± 12	175 ± 35	384 ± 60	657 ± 82	1,021 ± 105	1,501 ± 132	1,974 ± 161
above Highland Ditch	36 ± 12	185 ± 34	402 ± 59	684 ± 80	1,055 ± 102	1,544 ± 128	2,024 ± 156
above Coal Creek	36 ± 12	191 ± 32	413 ± 56	702 ± 76	1,083 ± 97	1,579 ± 123	2,071 ± 155
below Coal Creek	39 ± 11	198 ± 30	429 ± 52	738 ± 73	1,147 ± 97	1,661 ± 124	2,179 ± 158
above Meeker	37 ± 12	199 ± 31	433 ± 54	744 ± 73	1,152 ± 97	1,673 ± 125	2,199 ± 159

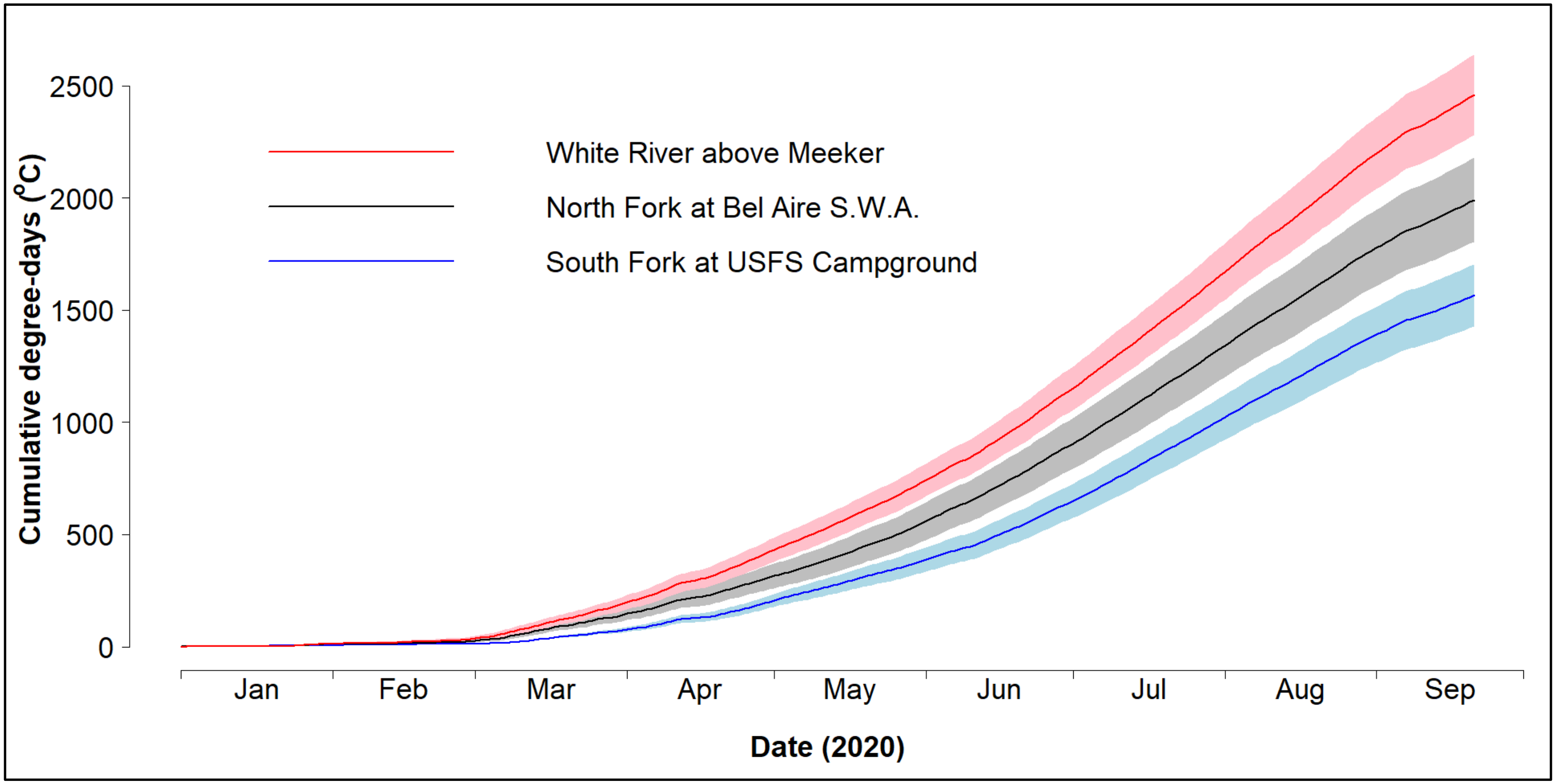


Figure 3. Comparison of degree-day accumulations at temperature monitoring sites in the upper, middle, and lower parts of the study area. Shaded areas represent 95% confidence intervals derived from cumulative sums of the upper and lower 95% confidence limits around each daily mean.

Although thermal requirements vary among coldwater fishes and even among sub-species (Bear et al. 2007; Brinkman et al. 2013; Rogers et al., *in preparation*), our fish-temperature metrics suggest that the extent of the upper White River was thermally suitable for coldwater fishes in both 2019 and 2020. Because 2020 was a relatively warm, dry year, it stands to reason that the upper White River typically is and has been suitable for coldwater fishes. However, the M30AT might drop below 9.0°C or exceed 18.0°C in the coldest and hottest of years at the upstream- and downstream-most sites, respectively. Further, if trends of a hotter, drier climate and earlier spring snowmelt continue (Stewart et al. 2005; Saunders et al. 2008), stream temperatures are likely to increase in the White River basin (Equation 1, this study). Of the coldwater species present in the upper White River, Mountain Whitefish might be the most susceptible to increasing stream temperatures, as their upper thermal tolerance is similar to, but slightly less than, that of CRCT and other trout (Brinkman et al. 2013). In the event segments of the upper White River become seasonally-unsuitable for coldwater fishes, we would expect them to seek out and occupy thermally-favorable habitats (Kaeding 1996; Petty et al. 2012; Hodge et al. 2017).

While temperature metrics like the M30AT and MWMT provide science-based criteria by which biologists can gauge habitat suitability for fishes, the requirement for days or weeks of retrospective data limits their application for real-time use. A different but well-supported fish-temperature metric might be appropriate for everyday consideration—namely, the daily maximum temperature. In consideration of all coldwater species in the upper White River, we suggest that stream temperature could become problematic when the daily maximum exceeds 21.6°C (Brinkman et al. 2013).

Our findings on stream temperature offer relatively little insight into the incidence of algal blooms on the White River. That temperatures are similar but algal taxa different between North and South forks (CPW 2017) suggests that temperature alone does not explain the relative scarcity of filamentous green algae in the South Fork. Research outside the basin has provided mixed evidence about potentially complex relationships between stream temperature and algae. Graham et al. (1982) found that the optimal growth temperature for *Cladophora glomerata* in Lake Huron was 13-17°C but that light level also played an important role in predicting growth. Mean daily stream temperatures in the upper White River were 13-17°C from approximately mid-June (2020) or mid-July (2019) to mid-September, depending on the site. Ralston et al.

(2014) found that degree-days, more so than temperature alone, explained both the timing and growth rate of algal blooms in an estuary and series of ponds. Specifically, higher January-February temperatures, and thus faster early-season accumulations of degree-days, were correlated with earlier algal blooms. Comparison of algal biomass to degree-day accumulations might reveal whether a similar relationship exists in the White River basin. In contrast to the positive temperature effects observed by Ralston et al. (2014), both Spaulding and Elwell (2007) and Kumar et al. (2009) observed that a particular freshwater alga favors cool if not cold, high-elevation streams. Prior reviews of the effects of temperature on algal growth, and of the ecology of *Cladophora glomerata*, reveal that optimal and lethal temperatures can vary not only among algal taxa (Singh and Singh 2015) but within algae species (Whitton 1970; Dodds and Gudder 1992). Accordingly, it is conceivable that different thermal regimes in the White River favor different algal taxa. To evaluate the effects of temperature on algae in the White River, one must consider and control for a suite of co-variates (e.g., discharge, nutrient concentrations)—a task well beyond the scope of this study. If stream temperature is a predictor of algal distribution and biomass in the White River, its significance might be revealed by the more comprehensive USGS analyses.

Given the importance of stream temperature to aquatic organisms (Lessard and Hayes 2002; Bear et al. 2007; Ziegler et al. 2013; Singh and Singh 2015) and the relative ease with which the data can be collected, long-term temperature monitoring seems like a logical way to track conditions in the upper White River. Our results suggest that by deploying data-logging temperature sensors at even a subset of the 20 sites monitored in this study, one could track spatial and temporal patterns in temperature. Our results also suggest that if the thermal regime immediately upstream of Meeker is sufficiently cool for coldwater fishes, so too will be all sites upstream. Ongoing research by USGS might shed light on the relationships between stream temperature and algae in the White River.

ACKNOWLEDGEMENTS

We thank all of the participating private landowners for their cooperation, D. Dauwalter (Trout Unlimited) and M. May (Colorado Parks and Wildlife) for providing comments that improved this report, M. Mayfield for GIS assistance, and Trout Unlimited and Colorado Parks and Wildlife for funding the study.

REFERENCES

Akaike, H. 1974. A new look at the statistical model identification. IEEE (Institute of Electrical and Electronics Engineers) Transactions on Automatic Control 19:716-723.

Anderson, N. J. 2000. Minireview: Diatoms, temperature and climate change. European Journal of Phycology 35(4):307-314.

Bear, E. A., T. E. McMahon, and A. V. Zale. 2007. Comparative Thermal Requirements of Westslope Cutthroat Trout and Rainbow Trout: Implications for Species Interactions and Development of Thermal Protection Standards. Transactions of the American Fisheries Society 136:1113-1121.

Bjornn, T. C., and D. W. Reiser. 1991. Habitat Requirements of Salmonids in Streams. Pages 83-138 in W. R. Meehan, editor. Influence of Forest and Rangeland Management on Salmonid Fishes and Their Habitats. American Fisheries Society Special Publication 19, Bethesda, Maryland.

Brinkman, S. F., H. J. Crockett, and K. B. Rogers. 2013. Upper Thermal Tolerance of Mountain Whitefish Eggs and Fry. Transactions of the American Fisheries Society 142(3):824-831.

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multimodel inference: a practical information-theoretic approach, 2nd edition. Springer-Verlag, New York.

Coleman, M. A., and K. D. Fausch. 2007. Cold Summer Temperature Regimes Cause a Recruitment Bottleneck in Age-0 Colorado River Cutthroat Trout Reared in Laboratory Streams. Transactions of the American Fisheries Society 136:639-654.

Colorado Parks and Wildlife (CPW). 2017. White River Algae Report on 2016 Data. Fort Collins, Colorado.

Dobos, M. E., M. P. Corsi, D. J. Schill, J. M. DuPont, and M. C. Quist. 2016. Influences of Summer Water Temperatures on the Movement, Distribution, and Resource Use of Fluvial Westslope Cutthroat Trout in the South Fork Clearwater River Basin. North American Journal of Fisheries Management 36(3):549-567.

Dodds, W. K. and D. A. Gudder. 1992. The Ecology of Cladophora. Journal of Phycology 28:415-427.

Dunham, J., G. Chandler, B. Rieman, and D. Martin. 2005. Measuring Stream Temperature with Digital Data Loggers: A User's Guide. USDDA Fs, RMRS General Technical Report RMRS-GTR-150WWW. March 2005.

Dunham, J., R. Schroeter, and B. Rieman. 2003. Influence of Maximum Water Temperature on Occurrence of Lahontan Cutthroat Trout within Streams. North American Journal of Fisheries Management 23:1042-1049.

Graham, J. M., M. T. Auer, R. P. Canale, J. P. Hoffman. 1982. Ecological studies and mathematical modeling of Cladophora in Lake Huron: 4. Photosynthesis and respiration as functions of light and temperature. Journal of Great Lakes Research 8(1):100-111.

Hodge, B. W., K. D. Battige, and K. B. Rogers. 2017. Seasonal and temperature-related movement of Colorado River cutthroat trout in a low-elevation, Rocky Mountain stream. Ecology and Evolution 7(7):2436-2356.

Isaak, D. J., S. J. Wenger, E. E. Peterson, J. M. Ver Hoef, D. E. Nagel, C. H. Luce,…S. Parkes-Payne. 2017. The NorWeST summer stream temperature model and scenarios for the western U.S.: A crowd-sourced database and new geospatial tools foster a user community and predict broad climate warming of rivers and streams. Water Resources Research 53(11):9181-9205.

Jacobsen, D., and R. Marín. 2008. Bolivian Altiplano streams with low richness of macroinvertebrates and large diel fluctuations in temperature and dissolved oxygen. Aquatic Ecology 42:643-656.

Kaeding, L. R. 1996. Summer use of coolwater tributaries of a geothermally heated stream by Rainbow and Brown Trout, *Oncorhynchus mykiss* and *Salmo trutta*. American Midland Naturalist 135:283-292.

Kaylor, M. J, S. M. White, W. C. Saunders, and D. R. Warren. 2019. Relating spatial patters of stream metabolism to distributions of juvenile salmonids at the river network scale. Ecosphere 10(6):e02781.

Kumar, S., S. A. Spaulding, T. J. Stohlgren, K. A. Hermann, T. S. Schmidt, and L. L. Bahls. 2009. Frontiers in Ecology and the Environment 7(8):415-420.

Lessard, J. L, and D. B. Hayes. 2002. Effects of elevated water temperature on fish and macroinvertebrate communities below small dams. River Research and Applications 19(7):721-732.

Lukacs, P. M., K. P. Anderson, and D. R. Anderson. 2010. Model selection bias and Freedman’s paradox. Annals of the Institute of Statistical Mathematics 62(1):117-125.

Maheu, A., A. St-Hilaire, D. Caissie, and N. El-Jabi. 2016. Understanding the Thermal Regime of Rivers Influenced by Small and Medium Size Dams in Eastern Canada. River Research and Applications 32(10):2032-2044.

Mayfield, R. B., and J. J. Cech, Jr. 2004. Temperature Effects on Green Sturgeon Bioenergetics. Transactions of the American Fisheries Society 133:961-970.

National Oceanic and Atmospheric Administration (NOAA). National Centers for Environmental Information. Available: https://www.ncei.noaa.gov/. (December 2020).

Null, S. E., M. L. Deas, and J. R. Lund. 2009. Flow and water temperature simulation for habitat restoration in the Shasta River, California. River Research and Applications 26:663-681.

Petty, J. T., J. L. Hansbarger, B. M. Huntsman, and P. M. Mazik. 2012. Brook Trout Movement in Response to Temperature, Flow, and Thermal Refugia within a Complex Appalachian Riverscape. Transactions of the American Fisheries Society 141(4):1060-1073.

R Core Team. 2020. R: A language and environment for statistical computing. Vienna, Austria. R Foundation for Statistical Computing.

Rahel, F. J., C. J. Keleher, and J. L. Anderson. 1996. Potential habitat loss and population fragmentation for cold water fish in the North Platte River drainage of the Rocky Mountains: Response to climate warming. Limnology and Oceanography 41(5):1116-1123.

Ralston, D. K., B. A. Keafer, M. L. Brosnahan, and D. M. Anderson. 2014. Temperature dependence of an estuarine harmful algal bloom: Resolving interannual variability in bloom dynamics using a degree-day approach. Limnology and Oceanography 59(4):1112-1126.

Roberts, J. J., K. D. Fausch, D. P. Peterson, M. B. Hooten. 2013. Fragmentation and thermal risks from climate change interact to affect persistence of native trout in the Colorado River basin. Global Change Biology 19:1383-1398.

Rogers, K. B., B. J. Sucher, B. W. Hodge, and C. A, Myrick. *In preparation*. Evaluating thermal tolerance in Cutthroat Trout of the southern Rocky Mountains.

Saunders, S., C. Montgomery, T. Easley, and S. Theo. 2008. Hotter and Drier: The West's Changed Climate. Available: http://www.rockymountainclimate.org/. (December 2020).

Schmitz, R. J. 1996. Introduction to Water Pollution Biology. Gulf Publishing Company. Houston, Texas.

Singh, S. P., and P. Singh. 2015. Effect of temperature and light on the growth of algae species: A review. Renewable and Sustainable Energy Reviews 50:431-444

Spaulding, S., and L. Elwell. 2007. Increase in nuisance algal blooms and geographic expansion of the freshwater diatom *Didymoshpenia germinata*: Recommendations for response. Federation of Fly Fishers and U.S. Environmental Protection Agency, Denver, Colorado.

Stewart, I. T., D. R. Cayan, and M. D. Dettinger. 2005. Changes toward Earlier Streamflow Timing across Western North America. Journal of Climate 18:1136-1155.

Underwood, Z. E., C. A. Myrick, and K. B. Rogers. 2012. Effect of acclimation temperature on the upper thermal tolerance of Colorado River cutthroat trout *Oncorhynchus clarkii pleuriticus*: thermal limits of a North American salmonid. Journal of Fish Biology 80:2420-2433.

United States Geological Survey (USGS). National Water Information System: Web Interface. Available: https://waterdata.usgs.gov/. (December 2020).

Wenger, S. J., D. J. Isaak, J. B. Dunham, K. D. Fausch, C. H. Luce, H. M. Neville, B. E. Rieman, M. K. Young, D. E. Nagel, D. L. Horan, and G. L. Chandler. 2011. Role of climate and invasive species in structuring trout distributions in the interior Columbia River Basin, USA. Canadian Journal of Fisheries and Aquatic Sciences 68(8):988-1008.

Whitton, B. A. 1970. Biology of Cladophora in Freshwaters. Water Research Pergamon Press 4:457-476.

Wittman, M. E., G. Annis, A. M. Kramer, L. Mason, C. Riseng, E S. Rutherford, W. L. Chadderton, D. Beletsky, J. M. Drake, and D. M. Lodge. 2017. Refining species distribution model outputs using landscape-scale habitat data: Forecasting grass carp and Hydrilla establishment in the Great Lakes region. Journal of Great Lakes Research 43:298-307.

Ziegler, M. P., S. F. Brinkman, C. A. Caldwell, A. S. Todd, M. S. Recsetar, and S. A. Bonar. 2013. Upper Thermal Tolerances of Rio Grande Cutthroat Trout under Constant and Fluctuating Temperatures. Transactions of the American Fisheries Society 142:1395-1405.