Stream channel restoration increases climate resiliency in a thermally vulnerable Appalachian river

Eric R. Merriam1,2, J. T. Petty1

We quantified stream temperature response to in-stream habitat restoration designed to improve thermal suitability and resiliency of a high-elevation Appalachian stream known to support a temperature-limited brook trout population. Our specific objectives were to determine if: (1) construction of deep pools created channel unit-scale thermal refugia and (2) reach scale stream channel reconfiguration reduced peak water temperatures along a longitudinal continuum known to be highly susceptible to summer-time warming. Contrary to expectations, constructed pools did not significantly decrease channel unit-scale summer water temperatures relative to paired control sites. This suggests that constructed pools did not successfully intercept a cool groundwater source. However, we did find a significant effect of stream channel restoration on reach-scale thermal regimes. Both mean and maximum daily stream temperatures experienced significantly reduced warming trends in restored sections relative to control sections. Furthermore, we found that restoration efforts had the greatest effect on stream temperatures downstream of large tributaries. Restoration appears to have significantly altered thermal regimes within upper Shavers Fork, largely in response to changes in channel morphology that facilitated water movement below major cold-water inputs. Decreased longitudinal warming will likely increase the thermal resiliency of the Shavers Fork main-stem, sustaining the ability of these key large river habitats to continue supporting critical metapopulation processes (e.g. supplemental foraging and dispersal among tributary populations) in the face of climate change.

Key words: climate change, cold-water ecosystems, salmonid conservation, stream restoration, thermal discontinuity, thermal refugia

Implications for Practice

• Channel reconfiguration to expedite water movement through key warming areas significantly decreased longitudinal warming within restored reaches.
• Decreases in longitudinal warming were greatest downstream of large cold-water tributaries, indicating network topology and thermal discontinuities strongly modulate benefits of channel reconfiguration.
• Efforts to create cold-water refugia through construction of deep pools that intercept groundwater were unsuccessful.
• Stream channel restoration may be used to increase thermal resiliency and salmonid conservation success within this and other large, cold-water river ecosystems impacted by climate change.

Introduction

Climate change is expected to result in widespread loss of cold-water habitats and dramatic changes in the distribution of associated cold-water species (Isaak et al. 2015). Fortunately, many small mountain streams are expected to be resilient to ambient warming under climate change (Snyder et al. 2015; Isaak et al. 2016). However, large-river systems that connect small tributaries are much more vulnerable to ambient warming (Merriam et al. 2017). Loss of large-river habitats may have important riverscape-scale consequences by reducing access to supplemental foraging habitats (Petty et al. 2014) and increasing the likelihood of local extirpation through population isolation (Letcher et al. 2007).

Recent work has begun to elucidate the complex local- (e.g. groundwater; Snyder et al. 2015), network- (e.g. network topology; Ebersole et al. 2015), and regional-scale (e.g. precipitation; Merriam et al. 2017; Santiago et al. 2017) factors controlling thermal vulnerability to climate change. There is also a growing body of literature suggesting strategic conservation and restoration efforts, such as riparian restoration and structural enhancement or alteration (Hester et al. 2009; Sawyer et al. 2011; Justice et al. 2017), can improve thermal suitability of degraded larger-river systems. However, experimental efforts to quantify the extent to which natural controls...
and complexities modulate thermal benefits of conservation and restoration actions have been limited (but see Beechie et al. 2013 and Justice et al. 2017 for modeling studies), despite recent calls for such efforts (Kausal et al. 2010).

We provide one such analysis within the upper Shavers Fork in West Virginia, U.S.A. Upper Shavers Fork is a large-river stream network (117 km² basin area) that supports one of only a few known brook trout metapopulations in the southern portion of its range (Pett et al. 2012; Aunins et al. 2015). Shavers Fork brook trout spawn in small, cold-water tributaries connected by a large-river main-stem (Pett et al. 2005). In addition to serving as a dispersal corridor, the Shavers Fork main-stem serves as supplemental foraging habitat wherein brook trout can avoid density-dependent resource limitation within tributaries and maximize growth (Huntsman & Pett 2014; Pett et al. 2014). However, these large-river habitats currently exist on the edge of thermal suitability, and climate change is expected to result in greater spatial and temporal discontinuity of suitable habitat throughout much of the year (Merriam et al. 2017).

A 7-km habitat enhancement and restoration project was implemented along the Shavers Fork main-stem in 2012 with the goal of improving habitat suitability for native brook trout. Mitigating historic (i.e. riparian loss and stream widening via land use activities) and future (i.e. climate change) thermal degradation represented the overriding objective of the restoration project (Trego et al. 2019). Specifically, the restoration was designed to: (1) decrease longitudinal warming by narrowing the stream channel and expediting water movement through key warming areas and (2) increase availability of thermal refugia through construction of deep pools that intercept groundwater. We provide a direct assessment of thermal response to main-stem restoration. We do so within the context of spatial (i.e. thermal discontinuities associated with major tributary inputs) and temporal (i.e. increased precipitation under climate change) complexities known to influence thermal suitability and resiliency within Shavers Fork (Merriam et al. 2017).

**Methods**

**Study Area**

The upper Shavers Fork is a high-elevation (originating at approximately 1,350 m) stream network located within the Monongahela National Forest in east-central West Virginia (Fig. 1). The Shavers Fork is a tributary to the Cheat River. Land cover is predominantly mixed deciduous-coniferous forest with abundant red spruce (*Picea rubens*). Shavers Fork is influenced by contemporary (residential and commercial development) and legacy (large-scale timbering and associated railroad development) land use activities that have reduced overall habitat quality and complexity.

Habitat enhancement and restoration efforts were designed to address the following habitat deficiencies along a 7-km segment of river downstream of Rocky Run (Fig. 1): (1) overwidened areas lacking a defined thalweg and highly susceptible to stream warming; (2) a general lack of deep pool habitats and structural complexity; and (3) unstable stream banks resulting from a lack of stream access to the floodplain in critical areas. Key restoration and enhancement measures included wing deflectors and thalweg enhancement designed to narrow the channel and increase water velocity through key warming areas (Fig. 2). Restoration also included construction of j-hook structures to alleviate bank erosion in key areas and increased availability of pool habitat (Fig. 3). Constructed pools were also designed to decrease temperature and create thermal refugia through interception of groundwater. All restoration actions increased the amount of suitable physical habitat for brook trout (i.e. deep, high velocity habitats adjacent to cover; Hansbarger et al. 2008).

**Restoration and Longitudinal Warming**

We monitored hourly summer (1 June - 31 August) stream temperatures at 12 sites distributed along the Shavers Fork longitudinal continuum (Fig. 1). Sites were strategically located to capture key reach-scale warming and cooling (e.g. downstream of major tributaries) areas. Five sites were located within the 4.5-mile restoration reach (i.e. restored; Fig. 1). Four sites were located upstream (i.e. upstream control) and three sites downstream (i.e. downstream control) of the restoration reach (Fig. 1). We collected data 2 years prior to (2010–2011) and 5 years following (2013–2017) restoration. We excluded data from 2012 due to influence from habitat restoration activities. This resulted in a total of 74 years of data across all 12 sites, with the number of years of data for a single site ranging from 4 to 7 (Table 1). We randomly assigned loggers along the continuum to control for any systematic bias in the loggers. The before-after-control-impact design also ensured that any temperature differences observed would be the result of the effects of restoration rather than differences in the loggers themselves.

Water temperatures were recorded using HOBO Water Temp Pro v2 data loggers (manufacturer-specified accuracy of ±0.21°C and resolution of 0.02°C, Onset Computer Corporation, Pocasset, MA, U.S.A.) anchored directly to the stream bed in mid-channel locations with moderate turbulence so as to encourage mixing and prevent localized effects of groundwater upwelling. We reviewed field notes for any indication of anomalies during data retrieval and visually compared temperature readings between nearby sites to identify and remove temperature readings from loggers that may have become dewatered (Sowder & Steel 2014). We compiled hourly data into mean and maximum daily stream temperatures for each site. Longitudinal temperature change was calculated by subtracting mean and maximum daily stream temperatures at each site from the next downstream site. Thus, positive and negative values indicate longitudinal warming and cooling, respectively. Longitudinal differences provided a measure of temperature change normalized with respect to variation in climatic and flow conditions known to influence stream temperatures within this and other stream networks (Merriam et al. 2017; Weber et al. 2017).

We used a hierarchical mixed effects model within a before-after-control-impact assessment framework to test for effects of restoration treatment (i.e. restored, and upstream and
Temperature response to stream restoration

Figure 1. Location of the upper Shavers Fork (uSF) watershed (WS) within West Virginia. Location of the 12 study sites distributed along the Shavers Fork continuum are shown with respect to whether they are located within the restored, upstream control, or downstream control river sections. Longitudinal sites are numbered consecutively from the upstream-most (1) to downstream-most site (12). Longitudinal sites with paired focal channel unit loggers are indicated. Site numbers reflect those presented in Table 1.

downstream control), time (i.e. pre- [2010–2011] and post- [2013–2017] restoration) and their interaction on longitudinal changes in mean and maximum daily stream temperature. Longitudinal changes in stream temperature were $x^\frac{1}{2}$ transformed to meet assumptions of normality. We included site and year as random effects (i.e. blocking factors) to account for site-specific characteristics affecting stream temperature response to restoration (e.g. groundwater influence and stream size) and inherent differences among years (i.e. climatic differences affecting stream temperature). We excluded differences between sites 4 and 5 and sites 9 and 10 because these represent zones of transition between restored and control sections. All statistical analyses were performed in Program R (R Core Team 2015). We used functions in package “lme4” (Bates et al. 2015) and “lmerTest” (Kuznetsova et al. 2017) to construct and assess hierarchical mixed effects models.

Restoration and Availability of Thermal Refugia

We deployed pairs of HOBO Water Temp Pro v2 data loggers to evaluate if temperatures in constructed pools decreased...
as expected. For each of the three constructed pools included in our evaluation at locations 5, 7, and 9 (Fig. 1), we deployed one temperature logger in the pool and one temperature logger a short distance upstream of the pool (122–300 m). In addition, one temperature logger at location 7 was also deployed in a nonpool channel unit slightly downstream of the constructed pool to serve as a control for these comparisons. We randomly assigned loggers in the paired study design to control for systematic bias in the loggers themselves. We used functions in package “stats” (R Core Team 2015) to conduct paired t tests to test for significant differences in mean and maximum daily temperatures between paired loggers. We compared daily and hourly stream temperature time series to assess potential effects of constructed pools on timing and magnitude of thermal fluctuations.

Results

Restoration and Longitudinal Warming

Linear mixed effects models identified a significant interaction between restoration treatment (i.e. restored, upper control, and lower control) and time (i.e. pre- and postrestoration) on longitudinal differences in both mean and maximum daily stream temperatures. We observed a significant difference between pre- and postrestoration mean \( t = -11.3, p = 0.000 \) and maximum \( t = -5.84, p = 0.000 \) daily temperatures within restored sites as compared to upper control sites (Table S1). We also observed a significant difference between pre- and postrestoration mean daily stream temperatures within lower control as compared to upper control sites \( t = -5.84, p = 0.000 \); however, the difference in mean
Temperature response to stream restoration

Figure 3. Aerial photo showing j-hook structures designed to alleviate stream bank erosion and increase availability of pool habitat (Photo by P. Kinder).

Table 1. Basin area (km²), years for which hourly summer (6/1–8/31) stream temperature data were collected, and sample size (n; days of data) for the 12 sites used to analyze patterns in longitudinal warming, as well as the four paired sites used to assess channel unit-scale thermal refugia. Treatment refers to whether longitudinal sampling sites are within the restored, upper control, or lower control river sections, and whether paired loggers were located in constructed pools or control channel units. Site numbers reflect those presented in Figure 1.

| Site | Treatment       | Basin area | Years (no.)                      | n  |
|------|----------------|------------|---------------------------------|----|
| 1    | Upstream control | 20.7       | 2010–11; 2013–17 (7)            | 643|
| 2    | Upstream control | 27.9       | 2010–11; 2013–17 (7)            | 643|
| 3    | Upstream control | 29.5       | 2010–11; 2013–17 (7)            | 634|
| 4    | Upstream control | 31.7       | 2010–11; 2013–17 (5)            | 643|
| 5    | Restored        | 38.7       | 2010–11; 2014–15; 2017 (5)      | 450|
| 6    | Restored        | 41.1       | 2010–11; 2013–15; 2017 (6)      | 551|
| 7    | Restored        | 43.0       | 2010–11; 2013–15; 2017 (6)      | 542|
| 8    | Restored        | 43.8       | 2010–11; 2013–17 (7)            | 643|
| 9    | Restored        | 59.4       | 2010; 2013; 2016; 2017 (4)      | 344|
| 10   | Downstream control | 65.1   | 2010–11; 2014–17 (6)            | 542|
| 11   | Downstream control | 89.1       | 2010–11; 2013–17 (7)            | 643|
| 12   | Downstream control | 117.4     | 2010–11; 2013–17 (7)            | 615|
| 5    | Constructed pool | 38.7       | 2014–15; 2017 (3)               | 269|
| 7    | Constructed pool | 43.0       | 2013 (1)                        | 92 |
| 7    | Control         | 43.0       | 2013–15 (3)                     | 268|
| 9    | Constructed pool | 59.4       | 2016–17 (2)                     | 182|

daily temperatures observed in restored sites postrestoration was 2.7× greater than for lower control sites (Table S1). Restoration had the greatest effect on longitudinal warming between sites 5 and 6: average differences in mean and maximum daily stream temperatures pre- and postrestoration were 0.7°C and 1.3°C lower (Fig. 4). Average longitudinal change in maximum daily temperature also decreased considerably between sites 8 and 9 (0.6°C) (Fig. 4). Both reaches exhibiting the greatest change were immediately downstream of major tributary inputs (i.e. Rocky Run, Second Fork; Fig. 1).

Restoration and Availability of Thermal Refugia

Constructed pools had significantly higher mean and maximum daily temperatures as compared to upstream paired loggers
Temperature response to stream restoration

Figure 4. Average longitudinal change in mean (top) and maximum daily (bottom) stream temperatures along the Shavers Fork continuum pre-(2010–2011) and post- (2013–2017) restoration. Site numbers correspond to those presented in Table 1 and Figure 1. The shaded area represents the extent of restoration. Arrows denote major tributary inflows.

Discussion

In-stream habitat restoration appears to have successfully altered stream temperature regimes within the Shavers Fork main-stem at the reach scale, but not the habitat unit scale. We documented a significant decrease in longitudinal warming pre- to postrestoration within the restored river section—a pattern that was not observed in either the upstream or downstream control river sections. To our knowledge, ours is the first experimental study to document direct effects of in-stream habitat restoration and alteration on reach- and network-scale thermal profiles within a large river (but see Justice et al. 2017 for a simulation-based study). Moreover, our results suggest strategic implementation of similar restoration techniques within other large cold- to cool-water systems could help mitigate and offset effects of current and future thermal stressors, ultimately increasing the resiliency of these at-risk habitats and associated assemblages (Isaak et al. 2015).

We also demonstrated that thermal benefits of in-stream restoration are strongly dependent upon the natural context within which they occur. We observed the greatest decrease in warming downstream of major tributaries, where channel narrowing increased transport and decreased warming of cold-water inputs. These results add to an increasing number of studies documenting the importance of network topology and cold-water inputs on the thermal regimes of this (Merriam et al. 2017) and other larger-river systems (Kiffney et al. 2006; Rice et al. 2006; Ebersole et al. 2015; Fullerton et al. 2015). However, ours is the first study to consider and document thermal benefits of in-stream restoration within the context of major tributary inputs and associated thermal discontinuities and highlights the need to account for these complexities to maximize and realize potential benefits of restoration.

Efforts to intercept groundwater via construction of deep pools did not result in decreased water temperatures or creation of thermal refugia at the habitat unit-scale. We consistently observed higher temperatures in constructed pools as compared to upstream paired loggers—a pattern also observed between the control pair. Although we tried to minimize the distance between paired loggers (i.e. distances ranging from 122 to 330 m), these results suggest elevated temperatures within constructed pools relative to their upstream paired loggers may reflect natural increases along the thermal continuum. Elevated temperatures within constructed pools may also be a function altered hydrology (i.e. decreased velocity and increased residence time) and associated increased susceptibility to warming (i.e. radiant heating and thermal exchange with the ambient air)—processes observed following construction of beaver dams in other mountain streams (Majerova et al. 2015).

The lack of cooling within constructed pools within Shavers Fork supports a number of previous studies failing to document cooling associated with in-stream restoration efforts utilizing similar techniques, such as natural channel design cross vanes and j-hooks (Crispell & Endreny 2009; Hester et al. 2009). Failure to decrease temperatures in constructed pools could be due to limited subsurface flow paths sufficient to change temperatures at the channel unit-scale (Poole et al. 2008). Moreover, constructed pools within this study were excavated to bedrock,
Table 2. Site characteristics (number and name [see Table 1 and Fig. 1]) and results of paired t tests comparing mean and maximum daily stream temperatures between the four temperature logger pairs. Logger pairs are shown with respect to whether the focal channel unit is a constructed pool or control site. Differences in daily stream temperatures ($\Delta T [^\circ C]$) were calculated by subtracting the upstream logger from the downstream focal channel unit (i.e. constructed pool or control) logger. Thus, positive values indicate warmer temperature in focal channel units. Distance (dist.) between logger pairs is provided for reference. CI, confidence interval.

| Site        | Dist. (m) | Mean daily temperature | Maximum daily temperature |
|-------------|-----------|------------------------|--------------------------|
|             |           | $\Delta T$ (95% CI)    | $t$ | $p$ | $\Delta C$ (95% CI) | $t$ | $p$ |
| Constructed pools | 5 | 136 | 0.22 (0.05) | 9.11 | 0.00 | 0.46 (0.07) | 13.2 | 0.00 |
|             | 7 | 330 | 0.16 (0.01) | 23.4 | 0.00 | 0.31 (0.04) | 16.9 | 0.00 |
|             | 9 | 122 | 0.13 (0.02) | 14.4 | 0.00 | 0.09 (0.03) | 5.8 | 0.00 |
| Control site | 7 | 185 | 0.20 (0.02) | 26.3 | 0.00 | 0.46 (0.04) | 21.2 | 0.00 |

Figure 5. Time series plots of daily mean and maximum stream temperature at a constructed pool and paired control logger (site 9) during the summer of 2017 (top panel). Hourly temperatures during the seven warmest days of 2017 are also shown for the same logger pair (bottom panel).

potentially minimizing or eliminating hyporheic exchange and associated cooling potential (Pollock et al. 2009). It is important to note, however, that we measured water temperature at a single location within the deepest portion (i.e. mid-channel) of each pool. We chose this methodology in an effort to measure and characterize channel unit-scale thermal patterns and remain consistent with the objective of the restoration effort (i.e. create channel unit-scale thermal refugia). In doing so, however, we did not assess potential creation of thermally suitable microhabitats, which have been associated with lateral groundwater seeps within this (Petty et al. 2012) and other systems (Ebersole et al. 2001). Therefore, further research attempting to characterize the extent to which constructed pools increase the availability of thermally suitable microhabitats is warranted.

Restoration efforts within Shavers Fork were designed to increase habitat suitability for resident brook trout through creation of thermally and physically (i.e. deep, high velocity...
habitats adjacent to cover, Hansbarger et al. 2008) habitat (Trego et al. 2019). Brook trout use of restored pools within Shavers Fork appears to be modulated by nonnative brown and rainbow trout, whereby nonnative individuals displace small brook trout from restored pools and small and large brook trout from optimal microhabitats, including thermal refugia (Trego et al. 2019). Decreased warming throughout the restored river section will increase availability of, and minimize competition for, thermally suitable and highly productive large-river habitats. Increased access to suitable large-river habitats could help alleviate density-dependent regulation within tributaries, increasing the potential for greater brook trout productivity at the individual- and population-level (Pettigrew et al. 2012; Huntsman & Petty 2014; Petty et al. 2014). However, restoration could confer similar benefits to nonnative trout, increasing competition for optimal habitats (Fausch & White 1981; Hitt et al. 2017). Benefits of restoration to brook trout within Shavers Fork may only be fully realized in the absence of nonnative species (Trego et al. 2019).

Our study also has important implications for the conservation of native salmonids within other regions that utilize large, cold-water habitats vulnerable to climate change (e.g. bull trout in the Columbia River Basin; Rieman et al. 2007). This is particularly true for regions such as the Northwestern United States where mountain headwater streams are expected to be resilient to ambient warming under climate change (Isaak et al. 2015). Targeting restoration to take advantage of associated thermal discontinuities may help to preserve network connectivity and increase the resiliency of associated cold-water species.

In-stream habitat alteration and restoration will have the greatest benefit to thermal suitability and resiliency of larger river systems if designed to: (1) minimize longitudinal warming through narrowing the channel and expediting water movement and (2) account for and leverage the natural riverscape context (i.e. network topology and thermal discontinuities) within which the restoration will occur. It will also be critical that restoration efforts be designed within the context of future climate change. Within Shavers Fork, thermal benefits of restoration are expected to persist through the 21st century as a result of increased precipitation and streamflow that are projected to offset effects of increased air temperature (Merriam et al. 2017). In many systems, however, climate change may result in warming that exceeds short-term benefits of in-stream restoration or exacerbate other factors limiting target ecosystems and organisms (e.g. interspecific interactions, Taniguchi et al. 1998).

Acknowledgments

We would like to thank B. Huntsman and M. Tincher for assistance with data collection and management. We also thank P. Mazik, B. Nestor, and D. Hartman for administrative oversight and assistance. Funding for this study was provided by the West Virginia Division of Natural Resources and US Geological Survey. This research was partially supported by the National Science Foundation under Award Number OIA-1458952, the USDA National Institute of Food and Agricultural (Hatch project 0233616), and the West Virginia Agricultural and Forestry Experiment Station. Use of trade, product, or firm names does not imply endorsement by the U.S. government.

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Supporting Information
The following information may be found in the online version of this article:

Table S1. Results of mixed effects models.

Received: 7 January, 2019; First decision: 5 March, 2019; Revised: 15 May, 2019; Accepted: 16 May, 2019; First published online: 13 June, 2019

Coordinating Editor: Margaret Palmer