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Karst Terrain Promotes Thermal Resiliency in Headwater Streams

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Abstract: The response of stream ecosystems to climate change will depend in part on groundwater processes that reduce the sensitivity of streams to atmospheric conditions. We investigated the thermal sensitivity of streams across a gradient of groundwater inputs defined by karst terrain (carbonate parent materials) in the headwaters of the Potomac River basin in eastern North America. We collected stream temperature data and quantified thermal sensitivity for 30 sites from the relationship between daily mean water and air temperatures. Our analysis demonstrates that thermal sensitivity is lower for streams in karst terrain than elsewhere, and that the effect of karst terrain is more important than elevation or basin size. Our study indicates the importance of karstic groundwater in mitigating rising air temperatures and provides a simple and rapid method to quantify stream thermal resiliency that can be implemented in conjunction with watershed organizations and citizen science networks.

Keywords: Stream temperature; karst; groundwater; climate change; thermal sensitivity; fish habitat

Introduction

Water temperature is a vital component of stream ecosystems, influencing nutrient dynamics, metabolic rates, animal behavior, and community composition (Ouellet *et al*. 2020). In North America, air temperatures have increased by 0.17 ºF per decade since 1901 (USGCRP 2017), and this compels new research to understand how stream ecosystems are responding to atmospheric changes. Here, we investigate the role of groundwater processes in regulating the thermal sensitivity of streams to air temperature change.

Groundwater-surface water interactions moderate the effects of air temperature on stream temperature by regulating conductive and convective heat-exchange processes (Kelleher *et al*. 2012; Johnson et al. 2017). For instance, localized upwelling of groundwater into streams increases the stability of stream fish communities over time (Hitt *et al*. 2023), affects fish life history traits (Hitt *et al.* 2022), and moderates the anticipated responses of coldwater fish to future warming (Snyder *et al*. 2015; Kaandorp *et al*., 2019). Such groundwater-surface water interactions are particularly important in karst terrain (carbonate parent materials) due to large aquifer volumes and extensive groundwater flow paths associated with bedrock fracture and dissolution (Kresic 2013). Although prior research indicates that streams in karst terrain are more hydrologically stable than streams of similar size elsewhere (White and Reich 1970; White 1977), streams in karst terrain exhibit spatially complex groundwater flow paths and geochemical signals (Shuster and White 1971; Kozar *et al*. 1991; Jones 1997) that motivate new research.

In this paper, we evaluate the role of groundwater for stream thermal resiliency to air temperature in the presence and absence of karst terrain. First, we demonstrate a methodology to estimate thermal sensitivity based on the relationship between daily mean air and water temperature observations. Second, we evaluate environmental covariates (elevation and basin size) as moderating effects in addition to karst terrain. We then discuss the utility of thermal sensitivity for conservation management, emphasizing the role of karst geology on thermal sensitivity of streams to climate change and the benefits of collaboration with watershed organizations.

Materials and Methods

Study area

We evaluated stream temperature in 30 sites within the headwaters of the Potomac River basin in eastern North America (Fig. 1). Sample sites included eight locations within the Sleepy Creek watershed (Berkeley County and Morgan County, WV) and 22 locations within the Antietam Creek watershed (Washington County and Frederick County, MD). The study area is located within the Ridge and Valley physiographic region with geological features characterized by resistant sandstone ridges and erosive limestones and shales comprising the valley floor (Evans *et al.* 2017). Land cover includes forested ridgelines with agriculture and limited urban development in the valleys (Irani and Claggett 2010).

Stream Temperature Survey

Volunteers with the Sleepy Creek Watershed Association and the Antietam – Conococheague Watershed Alliance collected stream temperature data during the summer of 2021. Site selection was determined by the watershed organizations. At each site, temperature gages (Onset ProV2, accuracy of +/- 0.2 °C) were deployed in perforated PVC cases secured to stream substrates (Snyder et al. 2015). Gages were programmed to record temperature every 20 minutes (Antietam) or 30 minutes (Sleepy Creek) from June 1 through August 31, 2021 (92 days). Water temperature data are available online from USGS ScienceBase.gov at https://doi.org/10.5066/P9Q2T48L (Antietam Creek watershed) and https://doi.org/10.5066/P9BEP9C0

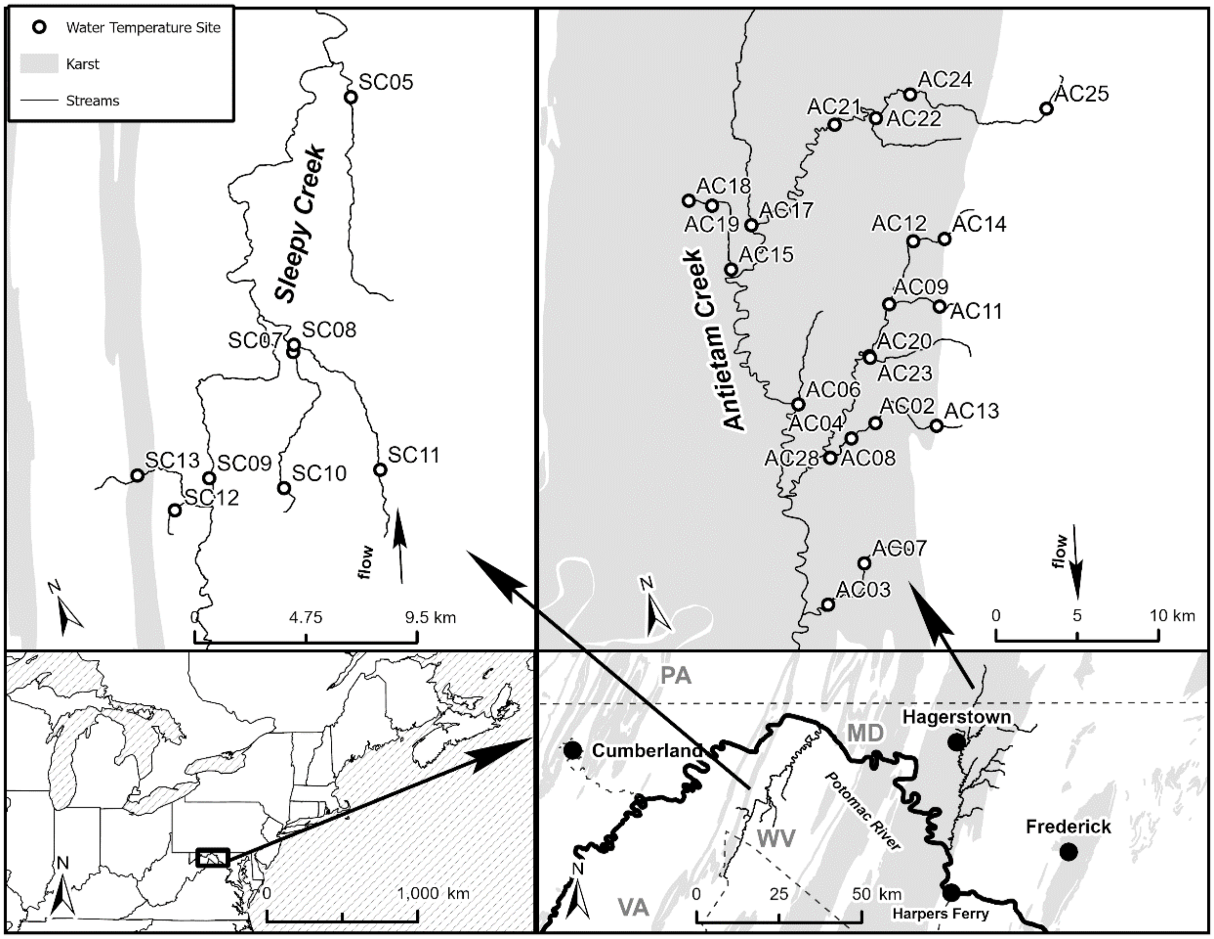

Figure 1. Study area map. Stream temperature sites are located within the Potomac River basin in eastern North America. Site codes are defined in Table 1. Grey regions indicate karst terrain (Weary and Doctor 2014).

(Sleepy Creek watershed).

We determined drying events through visual inspection for rapid stream temperature fluctuations before analysis (i.e., > 10 ºC diurnal flux, Sowder and Steel 2012). These events were rare, compromising 1.3% of all water temperature observations, and were excluded from analysis. Daily mean water temperature was calculated for each site. We then downloaded air temperature from a national dataset at a one km^2 spatial resolution (DAYMET, Thornton *et al.* 2022**)**. The dataset reports the maximum and minimum air temperature, and we estimated the mean daily air temperature as half the sum of daily maximum and minimum air temperatures for each study site **(**Thornton *et al.* 2022**)**.

Statistical Analysis

We quantified thermal sensitivity (TS) as the slope of the linear regression between daily mean water and air temperature (O'Driscoll and DeWalle 2006; Kelleher *et al.* 2012; Snyder *et al.* 2015; Johnson *et al.* 2020). We then quantified elevation, basin area, and karst presence for each site using 10-m digital elevation models in ArcGIS and the USGS Stream Stats Batch Processor version 5.3.04 (USGS 2019) for analysis as environmental covariates. We defined karst presence from site locations occurring on karst terrain as defined by a national karst atlas compiled from state geological maps (Weary and Doctor 2014). We compared median elevation and basin size in the presence and absence of karst with nonparametric Wilcoxon tests.

We then fit a regression tree model to evaluate the relative importance of elevation, upstream basin area, and karst presence/absence on TS. This machine-learning method uses recursive partitioning to minimize variation within groups (nodes) based on predictor variables. This statistical technique is useful for ecological analysis because it can account for nonlinear relationships and interactive effects that often characterize ecological systems (De'ath and Fabricus 2000). We avoided overfitting the model by requiring at least seven observations (sites) per node, and we evaluated optimal model structure based on minimum cross-validated error rates. We used R package "rpart" version 4.1.16 (Therneau and Atkinson 2022) to fit and evaluate the model. We conducted all analyses within R version 4.2.0 (R Core Team, 2022).

Table 1. Environmental covariates and thermal sensitivities. Sites are mapped in Fig. 1. Thermal sensitivity (TS) is defined as the slope of the linear regression between daily mean air and water temperature for each site. The y-intercept (y-int) and coefficient of determination (R^2) are given for each linear model. Site elevation (Elev) is given in meters, and upstream basin area (UBA) is given in hectares. Karst terrain presence (+) and absence (-) is given for the location of each site.

Watershed	Site code	Elev	UBA	Karst	TS	y-int	R^2
Antietam	AC02	150	1462	+	0.23	11.3	0.77
	AC03	113	6449	+	0.29	10.9	0.69
	AC04	138	1923	+	0.41	10.1	0.78
	AC06	130	1670	+	0.40	8.3	0.75
	AC07	128	1538	+	0.60	7.4	0.73
	AC08	138	2323	+	0.33	9.1	0.79
	AC09	160	3433	+	0.38	9.1	0.74
	AC11	239	236	+	0.46	7.9	0.58
	AC12	188	365	+	0.58	6.4	0.76
	AC13	231	178	-	0.34	9.2	0.63
	AC14	245	194	+	0.34	8.5	0.54
	AC15	149	1428	+	0.40	9.0	0.78
	AC17	149	8124	+	0.36	9.4	0.81
	AC18	177	363	+	0.31	10.5	0.69
	AC19	170	556	+	0.31	10.5	0.72
	AC20	151	3822	+	0.17	11.4	0.53
	AC21	160	6414	+	0.51	8.0	0.77
	AC22	171	1312	+	0.45	9.2	0.82
	AC23	152	1110	+	0.23	9.5	0.49
	AC24	185	2221	+	0.33	8.9	0.62
	AC25	416	318	-	0.56	7.4	0.83
	AC28	136	2323	+	0.50	9.0	0.80
Sleepy	SC05	191	1795	-	0.55	7.1	0.78
	SC07	200	5747	-	0.63	6.9	0.82
	SC08	201	2903	-	0.64	6.1	0.75
	SC09	220	7653	-	0.63	7.2	0.85
	SC10	226	4878	-	0.55	8.3	0.70
	SC11	246	1223	-	0.40	10.2	0.52
	SC12	236	147	-	0.63	6.7	0.85
	SC13	275	152	+	0.59	6.6	0.70

Table 2. Comparison of environmental conditions between karst and non-karst sites. Median basin area and elevation within karst categories are shown with associated Wilcoxon statistics.

Environmental variable	Karst present	Karst absent	*W*	*p*
Basin area (ha)	1538	2902	137	0.405
Elevation (m)	152	220	186	0.005

Results

Site elevations ranged from 113 to 416 meters (average 178, Table 1), and upstream basin area ranged from 147 to 8124 hectares (average 1026, Table 1). Sleepy Creek had seven of eight sites in non-karst terrain whereas Antietam Creek had 20 of 22 sites located within karst terrain (Table 1). Mean basin area was not significantly different for sites with and without karst terrain ($p = 0.41$; Table 2). Karst sites had a lower median elevation than sites without karst ($p < 0.01$; Table 2).

Linear models revealed substantial variation in TS among the study sites (Table 1). The highest TS value (i.e., least thermal resiliency) was observed at a site on the South Fork of Sleepy Creek (SC08, TS = 0.64), and the lowest TS value (i.e., greatest thermal resiliency) was observed at a site on Beaver Creek (AC20, TS = 0.17; Table 1). Linear models for TS (i.e., mean daily air-water temperature relationships) accounted for 49-85% of the observed variation in stream temperature (Table 1). TS was greater in the absence of karst terrain than the presence of karst terrain (Fig. 3) and was positively correlated with mean observed water temperatures (Spearman *rho* = 0.95, $p < 0.001$).

Regression tree results indicated that karst terrain was more important than elevation or basin area for predicting TS (Table 3; Fig. 4). Sites outside of karst terrain showed greater mean TS than sites within karst terrain (i.e., 0.56 versus 0.39, respectively; Fig. 4). In the presence of karst terrain, sites below 171 m in elevation exhibited the lowest TS levels whereas sites above this elevation (within karst terrain) showed higher TS values. The inclusion of karst in the model decreased the complexity parameter more than 10-fold the inclusion of elevation (Table 3), indicating the overriding importance of karst terrain for TS.

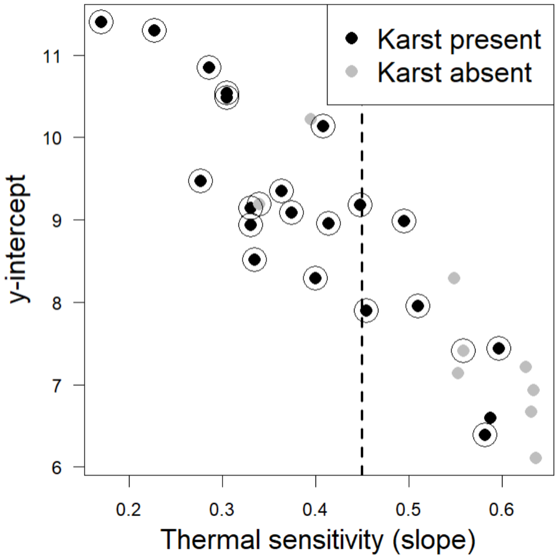

Figure 2. Thermal sensitivity of sampled streams in presence of karst terrain (black circles) and absence of karst terrain (grey circles). Outlines indicate sites in the Antietam Creek watershed. The most resilient sites are in the top-left quadrant (low sensitivity, high y-intercept), and the most sensitive sites are in the bottom-right quadrant (high sensitivity, low y-intercept). The dashed line indicates a threshold for groundwater-controlled sites (TS < 0.45) and atmospherically controlled sites (TS > 0.45) (Kelleher *et al.* 2012).

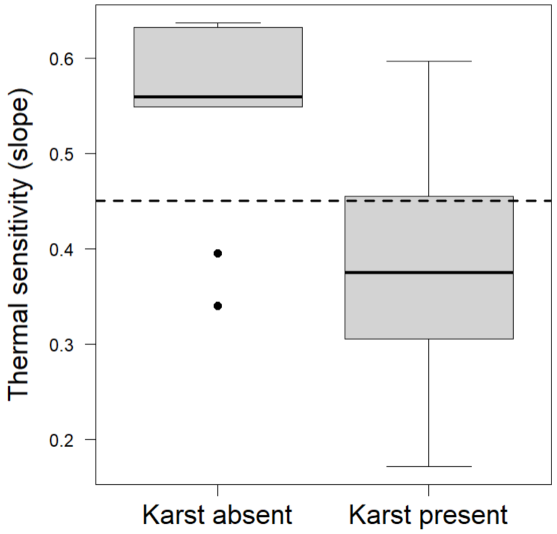

Figure 3. Boxplots for stream thermal sensitivity by karst terrain. The dashed line indicates a threshold for groundwater-controlled sites (TS < 0.45) and atmospherically controlled sites (TS > 0.45) (Kelleher et al. 2012). Two outliers are found within the karst absent sites. These outliers were SC11 (TS=0.40) and AC13 (TS=0.34).

Table 3. Regression tree results. The complexity parameter (cp) describes the minimum improvement necessary to include a new node in the model. The scenario with 0 splits represents the entire dataset (root node), and the scenario with 2 splits (3 leaf nodes) is plotted in Fig. 4.

Number of splits	cp	Relative error	Mean cross-validated error	Standard deviation of cross-validated error
0	0.356	1.000	1.070	0.182
1	0.034	0.644	0.816	0.172
2	0.010	0.610	0.816	0.172

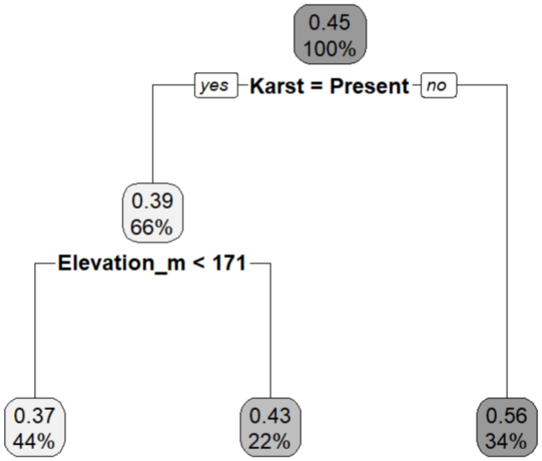

Figure 4. Regression tree model predicting stream thermal sensitivity (TS). Boxes represent nodes with mean TS (top value) and the percent of observations within that node (bottom value) due to karst presence/absence and elevation. Upstream basin area was pruned from the final model due to insignificance.

Discussion

Our study indicates the importance of groundwater in regulating the thermal sensitivity of streams to air temperature. We demonstrate that sites within karst terrain are more resilient to air–temperature change than sites lacking the large aquifers and springs associated with karst terrain. Moreover, karst terrain was more important than elevation or basin size in this regard.

Our results demonstrate the overall importance of karst terrain for thermal resiliency in streams, but we also observed heterogeneity among sites in this regard. For instance, TS ranged from 0.17-0.60 within karst sites (Table 3) and included six sites above the threshold for atmospheric controls on stream temperature (TS = 0.45, Kelleher *et al*. 2012; Fig. 2). This heterogeneity may be due to spatial variation in diffuse-type or conduit-type groundwater flow paths within the study area (McCoy and Kozar 2008; Evaldi *et al*. 2009). For example, dye tracing experiments in the Ridge and Valley region reveal groundwater systems with a mix of conduit-type and diffuse-type flows as well as preferential flow paths along major faults (Kozar *et al*. 1991). Although landform features such as sinkholes clearly define the presence of karst terrain (Doctor and Doctor 2012; Doctor *et al*. 2015), groundwater flow paths and travel times often are not predicted by such visible features (Kresic 2013). We also observed low TS values (i.e., < 0.45) in 2 sites that lack karst terrain (Fig. 2), suggesting the presence of localized groundwater upwelling without the influence of karstic aquifers or other controlling factors not addressed in this study like streamflow or riparian vegetation (Wissler *et al.* 2022). For example, similar spatial heterogeneity in TS has been reported from groundwater-surface water exchange in granitic and basaltic aquifers of the Blue Ridge region (Snyder *et al.* 2015).

Our results have implications for biological conservation and restoration planning. Groundwater exchange can provide refugia by reducing dewatering events and buffering temperature (Kelleher *et al.* 2012; Snyder *et al* 2015). Stability of fish communities over time is associated with low TS and with karst terrain to a lesser extent (Hitt *et al*. 2023). The simple analytical method demonstrated here can provide a rapid assessment of stream thermal resiliency for conservation planning.

Our results also help inform conservation and restoration planning for native brook trout (*Salvelinus fontinalis*), a coldwater–dependent fish species of ecological, cultural, and economic importance in Appalachia. For example, 18 of the 30 sample sites exhibited mean water temperatures below 20ºC (results not shown), a threshold for physiological stress and behavioral changes in brook trout (Chadwick *et al*. 2015; Hitt *et al*. 2017). However, habitat suitability also may be limited by spawning gravel availability and other conditions unrelated to water temperature or thermal resiliency, and we did not assess such habitat features in this study. We therefore interpret our results as an index of potential habitat suitability for native brook trout, and we recommend additional physical habitat assessments to evaluate site suitability for restoration planning. Our results also indicate the potential importance of riparian vegetation stream temperature in the absence of strong groundwater controls (Seavy *et al*. 2009; Roth *et al.* 2010; Singh *et al*. 2021).

We did not evaluate land use patterns in our study, but we note that urbanization is more extensive within the Antietam Creek watershed than within the Sleepy Creek watershed (i.e., Hagerstown within Antietam Creek watershed has a population > 43,000 whereas the Sleepy Creek watershed is comprised of small, incorporated towns; U.S. Census Bureau 2020). However, urbanization alone cannot explain our results because sites in the Antietam watershed exhibited more resiliency whereas urbanization is expected to increase thermal sensitivity and mean stream temperature (Kolath and Egemose 2023). Rather, our findings are consistent with prior research demonstrating a protective effect of karst groundwater on stream fish communities in urbanizing landscapes (Kollaus *et al*. 2015) and agricultural landscapes (Hitt *et al.* 2023). We recommend new research to evaluate the relative importance of thermal conditions relative to other attributes of stream physical habitat in this regard.

Inferences from our study are limited by the period of data collection (summer 2021) and therefore cannot account for interannual variation. Johnson *et al.* (2017) reported interannual variation in groundwater effects on stream temperature in the Blue Ridge region. The authors attributed this to spatial and temporal variation in precipitation and aquifer recharge dynamics. Nonetheless, it is likely that the observed effect of karst terrain in our study would be consistent over time because karst aquifers are expected to be much deeper and more stable than the relatively shallow aquifers investigated by Johnson *et al.* (2017). For instance, Briggs *et al.* (2022) estimated mean depth to bedrock for the study area of Johnson *et al*. (2017), and shallow depths (< ~2 m) were associated with dewatering and loss of surface flow in some cases. By comparison, karst terrain comprises much deeper aquifers (Kresic 2013) that can stabilize downstream flow and temperature (White 1977).

Leach and Moore (2019) observed a bias in empirical TS values due to effects of antecedent conditions that we did not evaluate. For instance, snowpack conditions were attributed to variation in TS that may not reflect groundwater dynamics or other mechanisms of thermal resiliency (Leach and Moore 2019). Their analysis specifically revealed variation within approximately 0.1 units for sites with similar elevation as in our study (350 m), and we evaluated this potential effect on our results with a simulation experiment. We added random variation to our estimated TS values from a normal distribution with mean = 0 and standard deviation = 0.1 across 100 replicate trials, and we found that each trial maintained the statistical difference we observed in the original data between karst and non-karst sites (results not shown). We therefore cannot attribute our results to antecedent effects as reported by Leach and Moore (2019), and we suggest that the absence of snowpack-dominated hydrology in our study area may explain the robustness of our results in this regard.

Upstream basin size (i.e., stream volume) was less important than karst terrain in our analysis of thermal sensitivity, and this suggests the importance of localized groundwater dynamics in regulating stream thermal responses to climate change. Although many river gages are available for analysis in West Virginia and across the United States (USGS 2023), small streams are underrepresented in this monitoring network (Deweber *et al.* 2014) and riverine conditions do not necessarily reflect conditions in headwater streams due to the importance of local geophysical processes (Kovach *et al.* 2019). As a result, it is often necessary to assess stream conditions and responses to climate change based on local observations, and this requires many new sites. Our analysis demonstrates a simple and intuitive approach to accomplish this goal in conjunction with watershed organizations and citizen science networks.

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