Instream wood increases riverbed temperature variability in a lowland sandy stream

Klaar, Megan J.; Shelley, Felicity S.; Hannah, David M.; Krause, Stefan

DOI:
10.1002/rra.3698

Received: 29 January 2020 | Revised: 10 July 2020 | Accepted: 13 July 2020
DOI: 10.1002/rra.3698

RESEARCH ARTICLE

WILEY

Instream wood increases riverbed temperature variability in a lowland sandy stream

Megan J. Klaar[1] | Felicity S. Shelley[2] | David M. Hannah[3] | Stefan Krause[3]

[1]School of Geography, University of Leeds, Leeds, UK
[2]School of Biological and Chemical Sciences, Queen Mary University of London, London, UK
[3]School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, UK

Correspondence
Megan J. Klaar, School of Geography, University of Leeds, Leeds, UK.
Email: m.j.klaar@leeds.ac.uk

Funding information
Natural Environment Research Council, Grant/Award Number: L003872/1

Abstract

The (re)introduction of wood into rivers is becoming increasingly popular in river restoration and natural flood management schemes. While instream wood is known to promote geomorphic and hydraulic diversity, the impact of wood in driving surface water-streambed exchange and subsequent streambed temperatures remains under-researched, particularly in lowland rivers. We make use of the occurrence of three naturally occurring wood structures in a small, lowland sandy stream to determine how the presence of wood alters the geomorphic, hydraulic and thermal properties of the streambed. Our results show that instream wood plays an important role in promoting localized geomorphic complexity and thermal variation in the streambed. Locations within and immediately downstream of wood structures displayed the highest temperature range and daily variation. Locations upstream of wood structures were characterized by weaker daily temperature variation, while areas without wood displayed relatively stable streambed temperatures, with little diurnal fluctuation. Our study indicates that at this lowland site, instream wood increased seasonal temperature extremes (increased summer and decreased winter temperatures) at shallow depths by enhancing infiltration of warmer (summer) and colder (winter) surface water. This reduction in thermal buffering is likely to have significant implications to streambed-dwelling communities and highlights that the thermal impacts of wood reintroduction in lowland rivers should be considered prior to river restoration.

KEYWORDS
hyporheic exchange flow, hyporheic temperature, large wood, lowland stream restoration, river thermal heterogeneity, thermal refugia

1 | INTRODUCTION

The promotion and restoration of natural process dynamics in rivers, in particular to mitigate anthropogenic impacts and climatic pressures, is an important component of river catchment science and management (Fryirs & Brierley, 2016; Wohl et al., 2005; Wohl, Lane, & Wilcox, 2015). Following years of active removal of instream wood from rivers as part of river and catchment management practices, there is an increasing body of evidence now suggesting that wood plays a vital role in creating and maintaining a range of ecosystem processes and functions (Grabowski et al., 2019; Hester, Hammond, & Scott, 2016; Krause et al., 2014). Instream wood has been shown to improve ecosystem structure, including provision of instream habitat (Bocchiola, 2011; Harvey, Henshaw, Parker, & Sayer, 2018; Roni, Beechie, Pess, & Hanson, 2014), and biological diversity (Pilotto, Bertoncin, Harvey, Wharton, & Pusch, 2014; Thompson et al., 2018).

Wood has also been shown to enhance hyporheic exchange flows (HEF) by forcing surface water into the streambed at and immediately upstream of the wooden flow obstacle, and subsequent hyporheic flow and upwelling downstream of the wood (Hester & Doyle, 2008; Sawyer, Cardenas, & Buttles, 2011).

Deploying instream wood for the promotion and restoration of HEF and enhancing the vertical connectivity between surface water and the hyporheic zone has been highlighted as a tool for improving river ecosystem health (Boulton, 2007; Burkholder, Grant, Haggerty, Khangaonkar, & Wampler, 2008; Hartwig & Borchardt, 2015; Hester & Gooseff, 2010). The mixing of surface and groundwater in the streambed creates strong physico-chemical gradients as well as thermal, biogeochemical, and ecohydrological conditions that are distinct from their surface water and groundwater neighbours (Hester, Cardenas, Haggerty, & Apte, 2017; Krause et al., 2011). These, in turn affect a wide range of ecosystem functions, including nutrient cycling and biogeochemical transformations (Lautz & Fanelli, 2008; Lazar et al., 2014; Shelley, Klaar, Krause, & Trimmer, 2017), sediment respiration and metabolism (Blaen et al., 2018) as well as ecosystem structure via the promotion of geomorphic complexity (England, Dobbek, Leeming, Gurnell, & Wharton, 2019; Harvey et al., 2018; Klaar, Hill, Maddock, & Milner, 2011).

Wood-induced HEF also creates spatial heterogeneity in streambed temperature regimes (Hester, Doyle, & Poole, 2009; Krause et al., 2011; Menichino & Hester, 2014; Sawyer & Cardenas, 2012). Streambed thermal conditions can have subsequent impacts on benthic ecology (e.g., fish spawning choice and success (Malcolm, Soulsby, & Youngson, 2002) and macroinvertebrate refugia (Wood, Boulton, Little, & Stubbington, 2010)), chemical transformation rates (Norman & Cardenas, 2014), and biological function (e.g., stream metabolism (Acuna, Wolf, Uehlinger, & Tockner, 2008), microbial processing (Nimick, Gammons, & Parker, 2011), species richness (Silva & Williams, 2005), and nutrient turnover (Nimick et al., 2011)). Temperature is therefore considered to be the "master variable" in determining hyporheic biogeochemical and ecohydrological processes (Webb, Hannah, Moore, Brown, & Nobilis, 2008). Heat transfer across the water–sediment interface and into the hyporheic zone is controlled by advection and conduction processes which pump surface water (advection) or diffuse heat (conduction) into the streambed (Arrigoni et al., 2008; Burkholder et al., 2008). In temperate environments, HEF usually results in cooler streambed temperatures in summer, and warmer hyporheic temperature in winter (Arrigoni et al., 2008; Caissie, 2006; Hannah, Malcolm, & Bradley, 2009; Hannah, Malcolm, Soulsby, & Youngson, 2004). This seasonal buffering provides important thermal microrefugia (Ashcroft, 2010) of particular importance to cold water species, including salmonids (Greer, Carlson, & Thompson, 2019; Malcolm et al., 2004).

To date, the majority of research on wood-induced HEF and its implications for thermal refugia in the hyporheic zone has focussed predominantly on small, upland gravel-bed rivers. These rivers are typically characterized by high hydraulic conductivities, which permit wood-induced HEF to penetrate the streambed to a greater degree than finer sediment or lower conductivity sediments typical of lowland streams (Hester et al., 2009; Krause et al., 2014; Magliozzi, Grabowski, Packman, & Krause, 2018). Meandering, finer sediment lowland rivers typically face a greater range of pressures than upland rivers. The flat fertile terrain (and high level of agricultural activity), proximity to large populations and past management mean that they are characterized as having increased point and diffuse pollution, altered flow, channelization and instream and riparian habitat degradation (Neal et al., 2012). Lowland rivers also typically have more extreme temperatures, owing to increased atmospheric input as a result of more stable discharges and decreased riparian shading (Poole & Berman, 2001b).

Given the differences in external pressures, environmental setting, and ecosystem integrity between upland and lowland rivers, it is not surprising to find an increasing body of evidence showing that wood restoration in lowland streams does not always confer the same benefits (outlined above) as observed in higher energy, upland streams (Daniels, 2006; Krause et al., 2014; Magliozzi et al., 2018). In order to address these opposing points, we made use of three naturally occurring wood structures to assess the wood's impact on instream structure and functioning within a sandy lowland river. More specifically, we undertook detailed geomorphic, hydraulic and thermal monitoring over the course of a year to assess how instream wood alters the streambed and temperature conditions which affect habitat diversity (ecosystem structure) and ecosystem functioning. We hypothesized that the instream wood in the investigated lowland stream would play an important role in promoting surface water downwelling into the streambed, resulting in increased thermal heterogeneity within the hyporheic zone. However, we also hypothesized that the finer sediments and more variable surface water temperatures found at our study site, typical of small lowland agricultural streams, would result in more extreme streambed temperatures, and therefore a reduction in thermal buffering within the hyporheic zone.

2 | METHODS

2.1 | Site description

Experimental investigations within this study focused on the Hammer Stream, a third order tributary of the lowland Western Rother river, West Sussex, comprising $\sim$25 km^2 of agricultural and forested land (Foster et al., 2019). The underlying Greensands and Mudstone geology result in the dominance of a fine sandy bed (D_{50} = 0.28 mm), with peat and clay lenses throughout the river bed and floodplain to a depth of approximately 1–2 m (Shelley et al., 2017). These impermeable layers were found to effectively isolate the study reach from the underlying aquifer and locally supressed groundwater upwelling (Dara, 2017), resulting in hyporheic flow being dominated by bedform and river bank geometry forced surface water downwelling.

A 60 m study reach bordered by patchy woodland on the west, and an open sparsely vegetated floodplain on the east containing three separate instream wood structures was selected for analysis (Figure 1). Wood deposition appeared to have occurred naturally and all of the structures covered >50 % of the channel width. The most

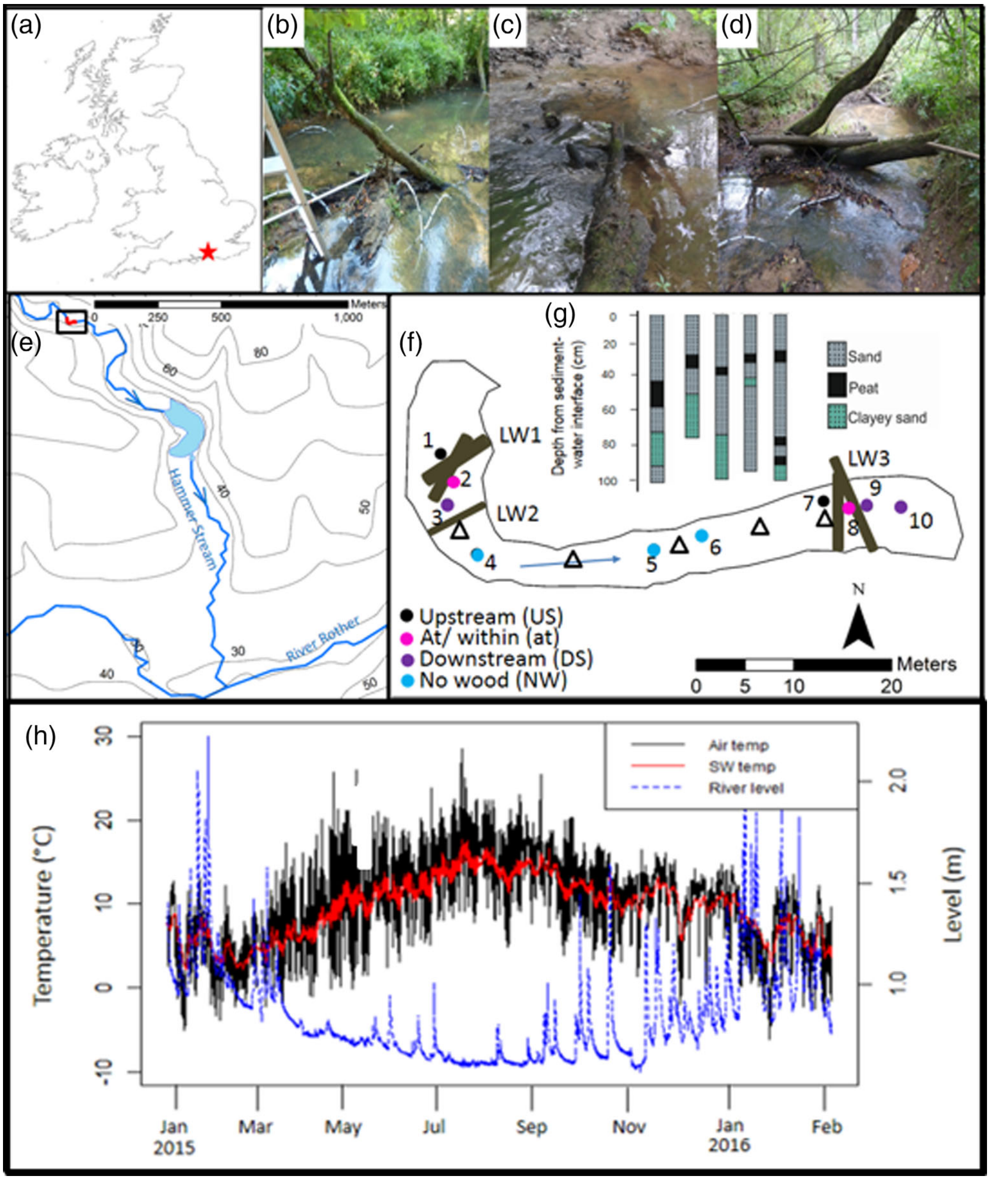

FIGURE 1 Map of the Hammer Stream, Sussex indicating (a) location within the UK, (b) upstream wood structure LW1, (c) wood structure LW2, (d) wood structure LW3, (e) relative location of the study reach (indicated in red within the box) relative to Hammer Pond and the River Rother, (f) position of instream wood and temperature lances (colour coded according to their relative position to wood) and corresponding temperature lance identification numbers and sediment cores (open triangle), (g) dominant sediment characteristics from core samples from upstream to downstream, (h) air and surface water temperature (°C) and river level (m) from December 2014–February 2016 [Colour figure can be viewed at wileyonlinelibrary.com]

upstream structure (LW1; Figure 1b) predominantly comprised a large log (approximately 4 m in length) embedded into the riverbed with numerous smaller pieces accumulated on the upstream section. A small depositional sandbar was evident on the downstream side of the wood. The second wood structure (LW2; Figure 1c) was located approximately 5 m downstream of LW1 and comprised a single large log embedded in the riverbed, perpendicular to the stream flow, creating a step-pool structure. The third wood structure (LW3; Figure 1d) comprised numerous ~1 m length wood pieces racked together in the centre of the channel, creating a large sandbar which at base flow, was often exposed.

2.2 | Data collection/instrumentation

Areas around the three wood structures were distinguished into upstream, at/within and downstream of wood categories to represent their spatial relationship to the wood. The 20 m section with no wood or other large structural elements was termed "no wood"; these delineations were used for subsequent categorical analyses as outlined below. Monitoring was predominantly focused around the wood, given the complexity of the structures and objectives of the study.

2.2.1 | Streambed temperature

Streambed temperature data was collected for 328 days (March 20, 2015–February 10, 2016) using custom made (Tempcon, Arundel, West Sussex, UK; Supplementary Plate 1) temperature lances for measuring stream bed temperatures at 5, 10, 20 and 30 cm depth from the bed surface, logging at 15 min intervals. The temperature lances (TLs) were constructed of steel pipes with a white powder coating in which Onset TM-CX-HD temperature loggers (−40° to 50°C range, accuracy ±0.25°C; Onset Computer Corporation, Bourne, MA, USA) were deployed flush to the outside of the pipe. The temperature loggers were connected to Hobo U12 outdoor loggers (Onset Computer Corporation, Bourne, MA, USA) which were installed on the river banks. A total of 10 temperature lances were placed in the streambed following the thalweg near the centre of the channel to monitor longitudinal profiles of streambed temperatures (Figure 1f). The sensors were calibrated prior to deployment by placing them into a bucket held at 20°C for 2 hr to determine correction values for each lance and every sampling depth which were subsequently applied in the data analysis. Lances were pushed manually into the streambed sediments, with the tops being flush with the bed surface. The exact location of the lances were determined using a total station as detailed below.

A separate surface water level, temperature and conductivity logger (Levelogger 3001 LTC Junior; 0.2 cm/±0.1°C/20 μS/cm accuracy, Solinst, Ontario, Canada) was installed at the bottom end of the study reach, protected from incident solar energy using a plastic pipe as a stilling well to house the logger. An air temperature and atmospheric pressure logger (Barrologger Edge, Solinst, Ontario, Canada) was placed on the river bank, adjacent to the surface water logger and out of direct sunlight, for subsequent atmospheric correction of the surface water logger. Surface water and atmospheric temperature data were collected every 15 min for a total of 418 days (December 19, 2014 – February 10, 2016).

2.2.2 | Streambed geomorphology

Georeferenced spatial topography data (minimum spacing 5 points per metre) were collected in June 2015 using a Leica Builder 300 total station to construct a digital elevation model of the study reach. A total of 364 points were surveyed throughout the 60 m study reach, which provided georeferenced position and height data relative to a known reference point. Inverse Distance Weighting (IDW; greater weight is given to values closest to the interpolated point) was used to interpolate the streambed surface between observation points using ArcMap (v 10.3.1, ESRI, California, USA) and to produce a digital elevation model of the study reach.

Seasonal changes in streambed elevation were measured as distance from the streambed sediment surface to the top of piezometers (see Shelley et al., 2017 for piezometer design) of a known length (1.5 m) at 40 georeferenced stationary piezometer locations throughout the study reach to monitor patterns of sediment erosion and deposition. Changes in streambed elevation at these locations were sampled in February, April, July and October 2015 and the elevation gain or loss calculated from baseline measurements of piezometer elevations in November 2014 to provide an indication of the temporal change in streambed elevation. These data were interpolated using IDW and differences in streambed topography between DEMs were calculated to produce seasonal maps of changes in topography. A minimum level of detection (LoD) was calculated as outlined by Smith and Vericat (2015) to distinguish between real topographic change and errors and uncertainties between DEMs. Data below the minimum LoD were omitted from the bedform change maps (Williams, 2012). Channel centreline transects at temperature lance locations were extracted from the bed elevation change maps to determine topographical change of the stream bed at each sampling season.

2.3 | Data analysis

Temperature data from the lances were visually inspected for erroneous data and errors prior to any subsequent analysis. 30 cm depth data at TL4 were excluded from all temperature analysis due to a faulty temperature probe, and data from 20 cm depth at TL10 were only used in the analysis from October 20, 2015 onwards due to an early problem with the probe. Data for TL5 had a later start date from April 17, 2015 onwards due to logger malfunction. All statistical analyses were performed in the R software package (v 3.4.1; R Core Team, 2015).

Due to the large amount of both spatial (4 depths at 10 locations) and temporal data (12 months) of streambed temperatures produced during the course of the study, all data were analysed by grouping into seasons represented as spring (March 20, 2015 – May 31, 2015), summer (June 1, 2015 – August 31, 2015), autumn (September 1, 2015 – November 30, 2015) and winter (December 1, 2015 – February 10, 2016) and at locations represented as "upstream of wood" (TLs 1&7; Figure 1), "at wood" (TLs 2 and 8), "downstream of wood" (TLs 3, 9 and 10) and "no wood influence" (TLs 4, 5 and 6). Grouping of TLs in this manner was validated using Kruskall–Wallis sum rank tests to ascertain any inherent variation between TLs which may preclude such grouping.

Differences in temperature between surface water and the streambed at the four location categories were assessed using effect size, calculated as Cohen's D (using the "*effsize*" R package) which is the difference in mean average temperature divided by the average of their pooled standard deviation (Cohen, 1988). Effect size, rather than traditional probability-based statistics (e.g., *ANOVA*) were used due to the large sample size (n > 25,000 points in all cases) which conflates Type I statistical errors (false positives) and thus prevents accurate probability-based statistical testing (Coe, 2002). Differences between streambed and surface water temperatures were considered to be significantly different when Cohen's D was >0.5 (medium effect; Cohen, 1988). Upper and lower confidence intervals at 95% confidence were calculated to provide an equivalent estimate of certainty. Coefficients of variation (ratio of standard deviation to the mean, expressed as a percentage) were calculated to express the dispersion of data around the mean which represents the stability and variation in temperature. Seasonal temperature duration curves at each depth were calculated to illustrate the thermal characteristics of the streambed (Hannah et al., 2009).

Diel (24 hr) temperature dynamics at each temperature lance and depth were analysed relative to their respective location relative to wood, to determine the average daily temperature ranges and dynamics experienced during each season. Average diurnal trends in streambed and surface water temperature were calculated for each hourly timestep at each of the four seasons to determine the magnitude of diurnal temperature fluctuation. The hottest (July 1, 2015; air temperature 21.6 °C, surface water temperature 17.7 °C) and coldest (January 20, 2016; −3.4°C air, 1.1 °C surface water temperature) recorded air and surface water temperature days (both of which occurred during prolonged extreme temperature periods; Figure 1) were analysed using a 6-hr time step to illustrate how extreme surface water temperatures influence streambed temperature in relation to the relative position of in-stream wood features. Stream bed topography data from July and October 2015 were used to represent the location of temperature probes in the streambed at the time of analysis. Streambed temperature was then interpolated for each 6-hr timestep using IDW between points (using default parameters) to illustrate diel temperature change. The shapefiles were then plotted in R using "*ggplot2*", "*akima*" and "*reshape*" packages.

3 | RESULTS

3.1 | Changes in streambed topography and sediment depth

Maps of seasonal dynamics of streambed topography (Figure 2) indicate a highly dynamic system with topographic lowering dominating in the downstream section over the course of the observation period. At the same time, a gradual accumulation of streambed sediment was observed adjacent to TLs 1–3 and LW1. The seasonal changes of streambed topography are best illustrated in longitudinal streambed profile (Figure 3), which clearly display the loss of sediment behind the downstream wood, while the largest pools remained stable, despite the levelling of topography in other areas.

Topographic change highlights that streambed sediments at and downstream of instream wood were more dynamic than at locations upstream of wood structures, while control locations show little change in streambed topography as most were below the minimum LoD. The most extreme changes to the streambed topography were observed during the early part of the year (February and April) with the accumulation of sediment at (e.g., TL8) and downstream (TLs 9 and 10) of instream wood. This resulted in the creation of mid-channel islands, which often rose above the water level and were later eroded in July and October. The deepest pools located upstream of instream wood were relatively stable in their position over time, despite topographic flattening in other areas of the streambed.

3.2 | Seasonal and spatial dynamics of streambed thermal conditions

For ease of communication, streambed temperature results are presented by season to highlight the spatial and temporal changes at these times in relation to surface water conditions.

3.2.1 | Spring

Average spring surface water temperature was 10.2 °C (air temperature 10.3 °C). Streambed temperatures at all locations and depths were not significantly different from surface water, as indicated by

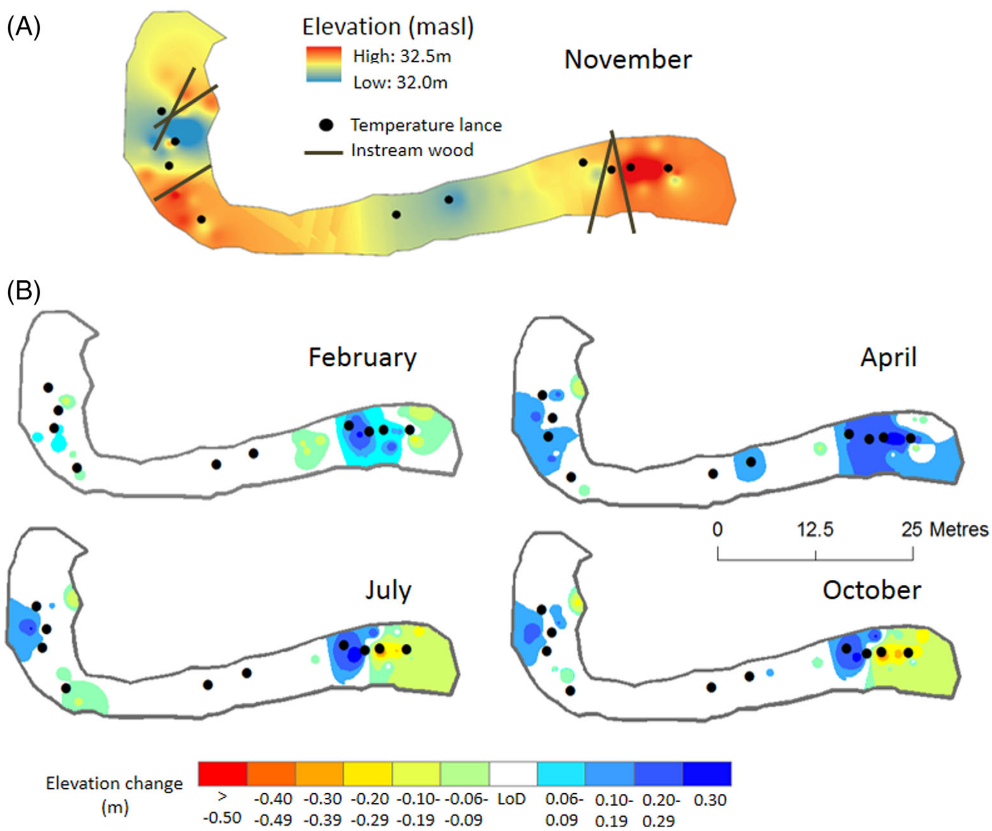

FIGURE 2 Seasonal variability in streambed topography (a) DEM of streambed elevation (November 2014); (b) change in streambed elevation from November 2014 to February, April, July and October 2015 [Colour figure can be viewed at wileyonlinelibrary.com]

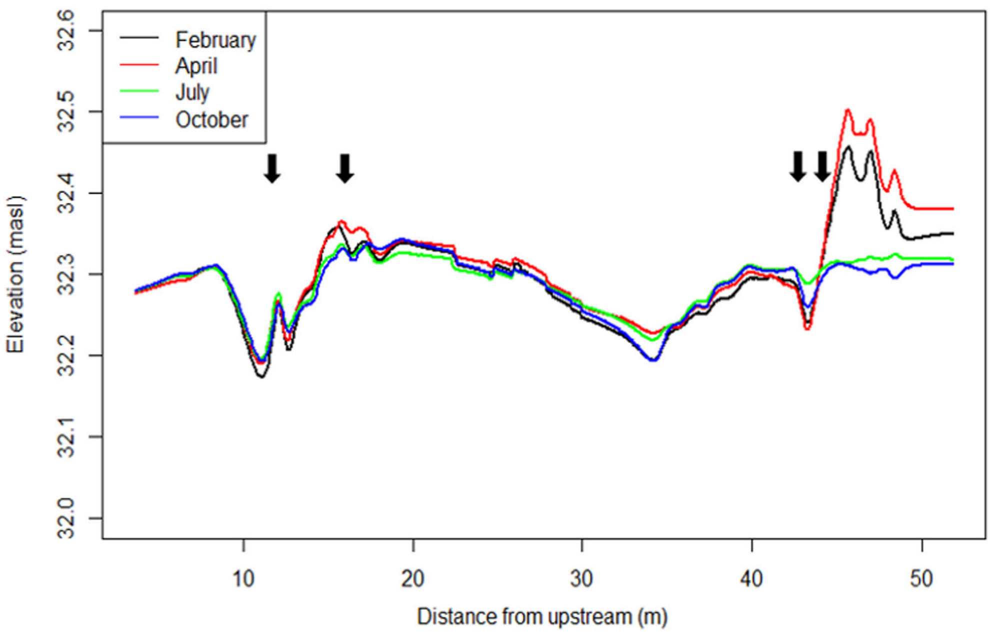

FIGURE 3 Seasonal longitudinal elevation changes to the river centre line February–October 2015. Black arrows represent the location of instream wood structures [Colour figure can be viewed at wileyonlinelibrary.com]

low Cohen's D (Table 1). The temperature duration curves (Figure 4) indicate that locations without wood (particularly TL5) were warmer than other locations during this time. This is also shown in the diurnal plots (Figure 5) which show a diurnal temperature pattern at 5 cm which weakens at 10 cm depth. TL2 (at wood) and TL9 (downstream of wood) in particular show a large diurnal fluctuation (2.5 °C range) in excess of that observed in surface water (1.5 °C range).

3.2.2 | Summer

The average summer surface water temperature was 14.1°C (air temperature 15.1°C). During this time, locations downstream of wood had the largest effect size (difference) to surface water temperatures to a depth of 20 cm, as did locations upstream and within wood at 5 cm depth. The temperature duration curves reveal a high variability in streambed temperature, particularly at locations downstream of wood which were characterized as being warmer than other locations at this time (to 30 cm depth) for a large majority of the time (approximately 80 % of the time to 30 cm depth at TL10), in contrast to sites with no wood which are much more stable as shown by the flat temperature duration curve. Diurnal patterns were strongest at depth in summer, with TLs downstream of wood showing a strong diurnal trend to 20 cm, and locations within wood following similar patterns to surface water (Figure 5).

3.2.3 | Autumn

Surface water temperature averaged 10.9°C (11.0°C air temperature) during autumn. TLs upstream and downstream of wood and in areas with no wood were significantly different from surface water temperatures. TLs located in areas without wood in particular exhibited the highest Cohen's D values (1 and 1.03 at 10 and 30 cm depth, respectively). The temperature duration curves suggest that areas without wood had higher and more stable temperatures than any other locations, down to 30 cm depth. Lances within and downstream of wood structures, on the other hand, display more variable and colder temperatures for a large percentage (50 %) of the time. Figure 5 reveals a weak surface water diurnal fluctuation, however TLs within and downstream of wood show some evidence of a diurnal response at 5 cm depth which is more pronounced than that of surface water. The three TLs located in areas without wood influence (the control reach) all display warmer average streambed temperatures at 10 and 30 cm depths.

3.2.4 | Winter

Trends in streambed temperature during winter were similar to those found in autumn. Average surface water temperature was 7.7 °C (air temperature 7.9 °C). TLs located upstream, downstream and at areas without wood influence all had significantly different average streambed temperatures at all depths in comparison to surface water, with the exception of the 5 cm depth downstream of wood. Temperature duration curves reveal stable streambed temperatures in comparison to other seasons; TL6 once again had warmer, more stable streambed temperature at 10 cm. All locations and depths displayed warmer average diurnal temperatures than surface water, particularly at locations upstream, downstream and without wood influence.

3.3 | Seasonal temperature extremes

More detailed analysis of the diel temperature fluctuations during the hottest and coldest days (Figure 6) shows that on the hottest

TABLE 1 Summary of seasonal average temperature and differences in mean temperature between surface water and (coefficient of variation, effect size [Cohen's D] and lower/upper confidence intervals) at four streambed locations and depths within Hammer Stream.

Depth (cm)		Spring					Summer					Autumn					Winter				
		Ave (°C)	CV (%)	D	Lower	Upper	Ave (°C)	CV (%)	D	Lower	Upper	Ave (°C)	CV (%)	D	Lower	Upper	Ave (°C)	CV (%)	D	Lower	Upper
SW (air)		10.2 (10.3)	17.5	-	-	-	14.1 (15.1)	9.4	-	-	-	10.9 (11.0)	14.4	-	-	-	7.7 (7.9)	29.5	-	-	-
US	5	10.8	16.7	0.32	0.311	0.319	15.0	8.8	**0.71**	0.697	0.706	12.2	10.8	**0.79**	0.790	0.799	9.3	20.3	**0.63**	0.625	0.636
	10	10.5	15.9	0.17	0.160	0.170	14.6	8.3	0.40	0.396	0.405	12.0	10.2	**0.64**	0.633	0.643	9.2	19.4	**0.57**	0.568	0.579
	20	10.4	15.6	0.10	0.097	0.110	14.5	8.3	0.31	0.307	0.320	12.0	9.8	**0.71**	0.699	0.712	9.2	18.2	**0.56**	0.557	0.570
	30	10.1	14.5	−0.06	−0.690	−0.054	14.0	7.7	−0.11	−0.114	−0.098	11.9	9.2	**0.69**	0.676	0.694	9.3	16.2	**0.59**	0.584	0.560
At	5	10.6	17.7	0.18	0.172	0.180	15.0	10.7	**0.54**	0.532	0.543	12.0	12.4	**0.72**	0.713	0.721	9.1	22.5	**0.58**	0.581	0.588
	10	10.4	16.6	0.09	0.085	0.091	14.4	9.4	0.24	0.240	0.249	11.5	12.3	0.37	0.367	0.373	8.6	22.2	0.33	0.322	0.329
	20	10.4	15.5	0.09	0.083	0.095	14.3	8.2	0.14	0.130	0.142	11.6	10.8	0.43	0.429	0.440	8.8	19.7	0.43	0.426	0.437
	30	10.2	14.9	−0.01	−0.015	−0.001	14.1	7.9	0.01	−0.001	0.013	11.7	9.9	**0.54**	0.531	0.546	9.0	17.7	0.51	0.508	0.524
DS	5	10.6	18.0	0.20	0.194	0.203	15.0	10.2	**0.59**	0.583	0.592	11.6	13.3	0.46	0.453	0.460	8.7	23.2	0.43	0.425	0.432
	10	10.7	17.1	0.26	0.253	0.263	15.2	9.7	**0.75**	0.741	0.752	12.0	12.4	**0.73**	0.725	0.734	9.1	21.4	**0.60**	0.598	0.607
	20	10.5	15.4	0.17	0.166	0.176	14.9	9.7	**0.54**	0.529	0.541	12.1	10.9	**0.80**	0.791	0.802	9.2	19.5	**0.62**	0.610	0.623
	30	10.3	15.2	0.02	0.013	0.025	14.5	8.8	0.27	0.268	0.280	12.0	10.1	**0.73**	0.726	0.739	9.3	17.8	**0.68**	0.673	0.689
NW	5	10.8	14.0	0.24	0.239	0.248	14.7	8.3	0.43	0.429	0.440	12.1	11.1	**0.76**	0.753	0.761	9.1	21.3	**0.56**	0.557	0.564
	10	10.6	13.8	0.12	0.112	0.123	14.6	8.6	0.41	0.406	0.420	12.4	11.0	**1.03**	1.018	1.033	9.6	19.7	**0.50**	0.493	0.505
	20	10.3	12.0	−0.09	−0.096	−0.082	13.6	7.9	−0.38	−0.388	−0.373	11.6	9.6	**0.50**	0.489	0.502	9.0	17.7	**0.85**	0.846	0.860
	30	10.5	11.8	−0.04	−0.047	−0.028	14.1	7.6	−0.38	−0.388	−0.373	12.4	8.1	**1.00**	0.992	1.012	9.7	14.8	**0.81**	0.803	0.822

Note: Figures in bold indicate where Cohen's D is >0.5 ("medium" effect size). Ave = average temperature; CV = coefficient of variation, D = Cohen's D; lower = lower confidence limit; upper = upper confidence limit.

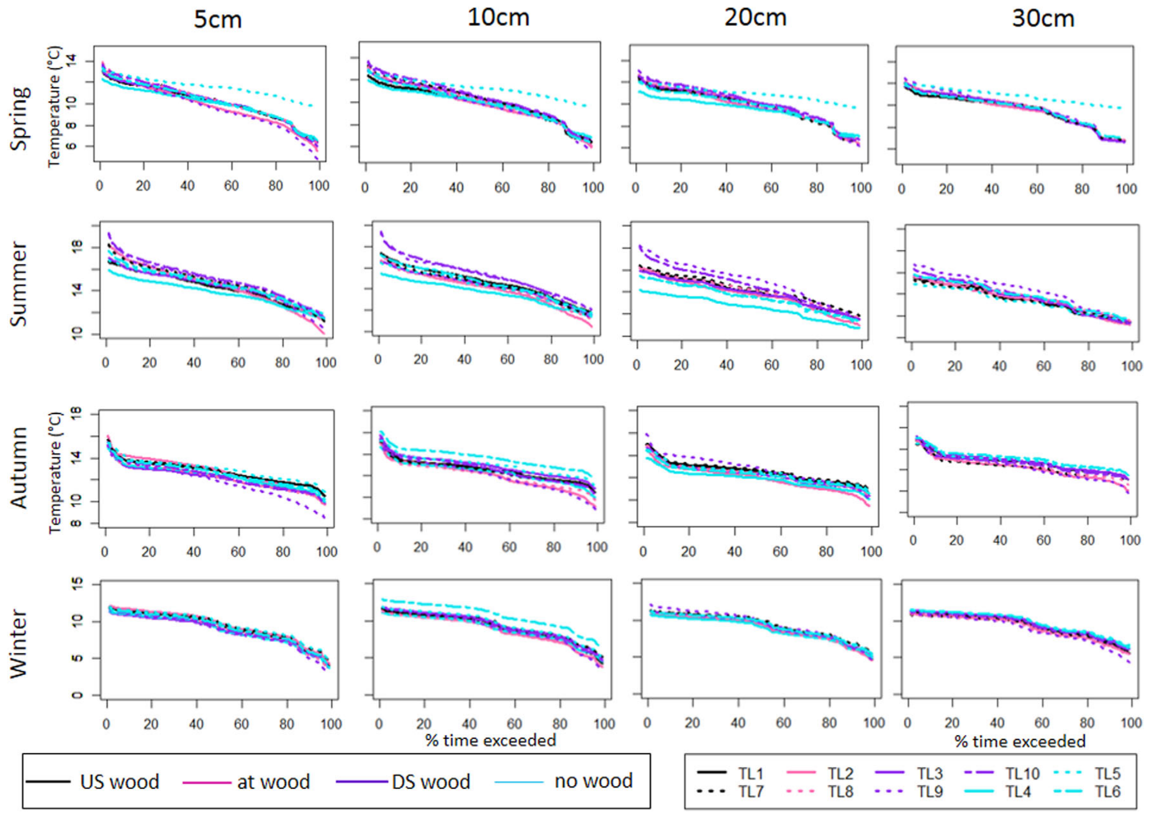

FIGURE 4 Seasonal temperature duration curves for different depths from 5–30 cm. Individual temperature lance data and relative position to instream wood are represented by the colour and line outline [Colour figure can be viewed at wileyonlinelibrary.com]

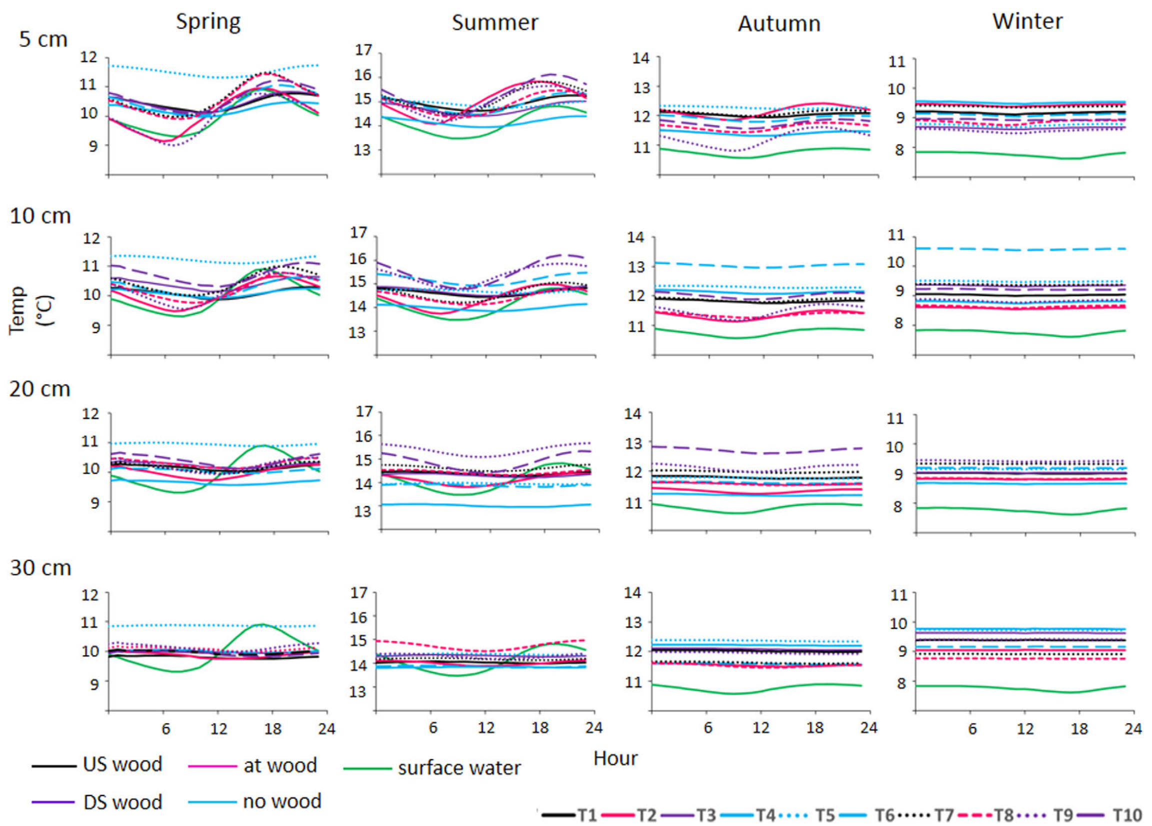

FIGURE 5 Diurnal plots of average hourly temperature at the four study depths and seasons. Individual temperature lance data and relative position to instream wood are represented by the colour and line outline [Colour figure can be viewed at wileyonlinelibrary.com]

day, there was a gradual increase in streambed temperatures to a maximum of 20 °C at 5 and 10 cm streambed depths, 18.3 °C at 20 cm and 16.4 °C at 30 cm depth from 1800–2400 hr at LW3 (right hand side of the figures) with a later increase in streambed temperature at LW1 & 2, peaking at 1800–2400 hr. Locations with no wood were characterized by smaller increases in temperature over the course of the hottest day, with peak temperatures (at 1800–2400 hr at TL6) of 17.8 °C at 5 cm, 17.1°C at 10 cm, 14.8 °C at 20 and 15 °C at 30 cm in contrast to the surface water average of 17.8 °C during the same time period. The range of streambed temperature during this time highlights the greater variability in temperature at and downstream of the wood, particularly at the most downstream section. Areas without wood influence remained relatively stable by comparison. An opposite pattern in temperature fluctuations were observed in January. During this time, the areas without wood maintained higher temperatures (day average of 3.9, 6.2, 5.8 and 6.8 °C at 5, 10, 20 and 30 cm depth, respectively, in comparison to 3.2 °C day average for surface water), while areas around instream wood and LW1 & 3 in particular displayed a decrease in temperature from 1200–2400 hr. The range of temperatures at this time were less variable, with the exception of the most upstream area between 0600 and 1200 hr.

A summary of topographic and thermal characteristics of the streambed in relation to wood position is provided in Table 2.

4 | DISCUSSION

A large number of previously published studies of wood impacts on the river environment have focused predominantly on high energy, course

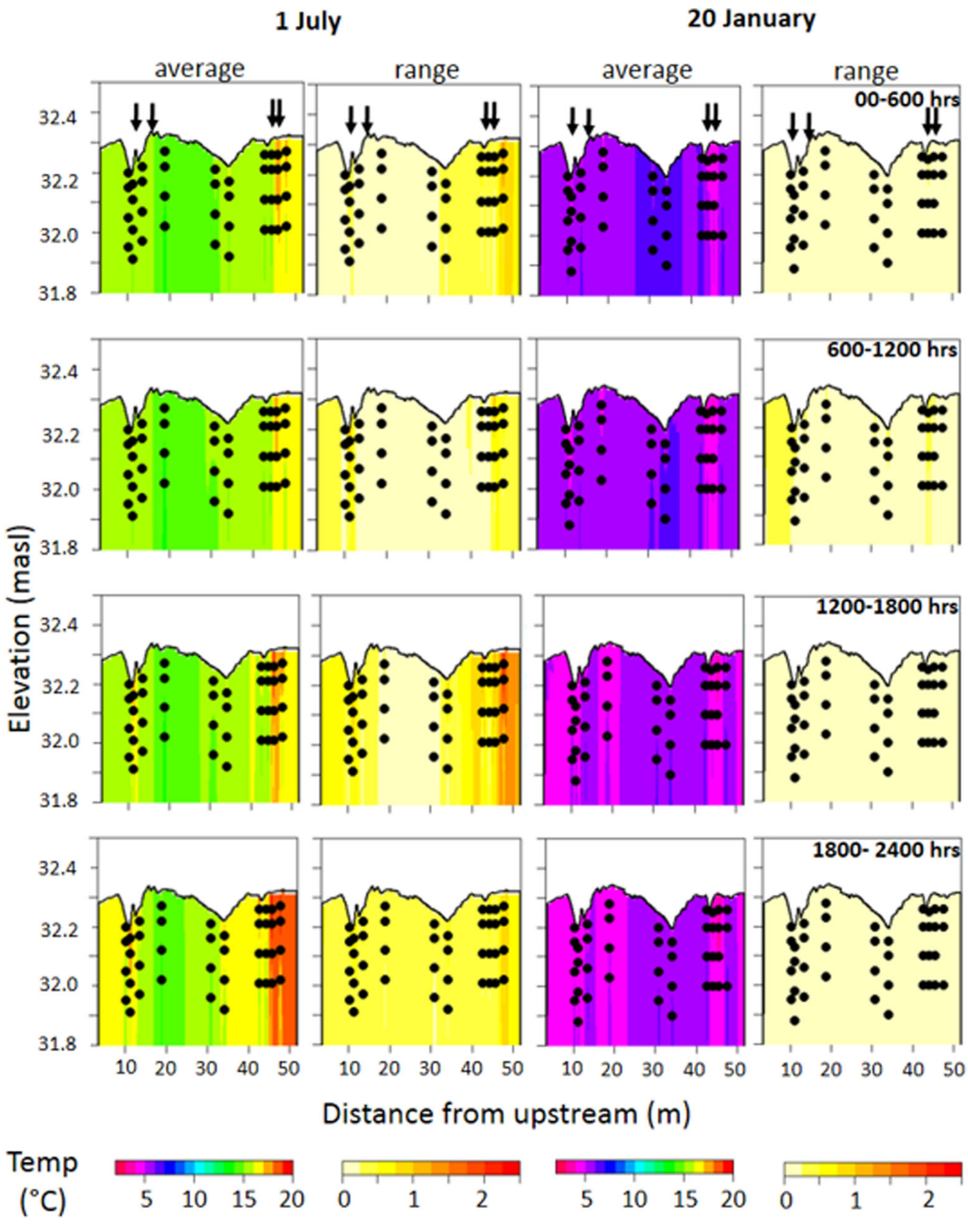

FIGURE 6 Six-hour average and range of streambed temperatures during the hottest (July 1, 2015) and coldest (January 20, 2016) days. The black circles represent the location of the temperature lance thermistors and the arrows indicate the location of instream wood structures (marked on the top figures only). Temperature lances are numbered sequentially from left to right [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Summary of topographic, seasonal, diurnal and seasonal extreme event temperature patterns at streambed locations relative to wood

	Upstream of wood	At/ within wood	Downstream of wood	No wood (control)
Topography	Seasonal changes but relatively stable	Sediment accumulation	Sediment accumulation (winter, spring), lowering in summer and autumn	Little change, all seasons
Average seasonal temperature	Weak connection with SW at all depths in autumn and winter; strong connection with SW in spring and summer	No significant difference to SW temps- strong connection, particularly at 10 & 20 cm depths	Strong SW connection at 5 cm	Significantly different from SW in autumn and winter. Stable temps. Colder than SW in summer at 5, 10, 20 cm
Diurnal temperature	Strong summer and spring diurnal trend to 10 cm	Strong diurnal trend to 10 cm in spring and summer	Strong diurnal signal in spring and summer to 10 cm depth, warmer than SW in summer and autumn to 20 cm depth	Weak SW signal at all seasons and depths
Extreme surface water events	Gradual SW signal response over time, peaking at 1800–2400 hr	Strong SW signal from 1200 hr to 30 cm depth	Strong summer temperature signal to 30 cm depth	Cooler (summer), warmer (winter) temperatures

SW = surface water.

grained catchments (Krause et al., 2014), with significantly fewer studies aimed at small agricultural sand-bed streams, which differ significantly in terms of character (gradient, sediment size and stream power) and management (Neal et al., 2012). This study aimed to provide a detailed assessment of the role of instream wood in altering streambed topography and temperature in a lowland sandy stream. Our results show that instream wood promotes localized geomorphic complexity, which increased HEF and thermal variation within the streambed; however, the timing and location of streambed temperature variability observed was markedly different than that previously reported in upland sites.

Monitoring of the seasonal dynamics of streambed topography revealed that the sandy streambed in the research area was highly mobile, with the presence of instream wood being particularly important in creating topographic variability by inducing forced scour and deposition. The wood was found to play an integral role in creating mid-channel bars and areas of fine sediment deposition which may otherwise be rapidly washed out (Smock, Metzler, & Gladden, 1989). Sediment accumulation behind the downstream wood structure (LW3) in winter and spring was gradually eroded again in summer (July) and autumn (October), likely due to late spring and summer storms highlighted in the stream level data of Figure 1. Our results support those of Mutz (2000), Mutz & Rohde, 2003) who have previously shown that wood was important in determining channel morphology and creating a number of pools and bars in a lowland sandy stream in Germany. As was observed by Mutz et al., we found that the influence of wood was spatially limited to areas close to the structures due to the slower flow velocities characteristic of lowland rivers. This enhanced geomorphic complexity results in increased HEF diversity and dynamics and subsequent dynamism of streambed habitat conditions. The creation of areas of sediment deposition around wood, for example the mid-channel bars downstream of LW3 also increase biocomplexity within the river environment (Gurnell, Tockner, Edwards, & Petts, 2005).

Seasonal streambed temperature patterns were found to vary according to relative proximity to wood. Locations within wood structures displayed the highest temperature range and daily variation. The shallowest streambed depths (5 and 10 cm depth) were characterized by a wide range of temperatures in spring and summer, including a strong diurnal signal and evidence of warmer temperatures in summer and colder temperatures in winter to 30 cm depth. These results are indicative of good connection to the surface water with forced surface water downwelling and strong HEF as a result of the presence of wood. Data from the hottest and coldest days further highlight the importance of wood in driving HEF and thermal variation into the immediate areas of the wood. Positions upstream of wood structures were characterized by a strong connection with surface water in spring and summer to 10 cm depth and relatively stable temperatures in autumn and winter at all four depths. This strong connection with surface water can also be seen in the vertical cross sections, when streambed temperatures gradually changed to reflect surface water temperature; getting warmer in summer and colder over the course of the day. The areas without wood influence were characterized by stable streambed temperatures, with little diurnal fluctuation or geomorphic dynamism. The diurnal plots and effect size analysis indicate that the streambed at these locations was often warmer than surface water or those locations associated with instream wood in autumn and winter, and cooler in spring and summer. These areas without wood are likely to rely on conduction and advection to transfer heat from surface water to the streambed rather than wood-induced HEF, resulting in the more stable temperatures observed.

Areas downstream of wood were variable in their response to daily and seasonal temperature fluctuations. TLs 9 & 10, which were located in a mid-channel sandbar created by the wood had large temperature variation, and evidence of warmer average daily temperature than surface water to a depth of 30 cm in summer, resulting in steeper temperature duration curves and average daily temperatures as shown in the diurnal plots. The build-up of exposed sediment downstream of wood at TLs 9 & 10 and exposure of the sediments above the water level allows these areas to receive increased atmospheric heat input, resulting in this sustained increase in summer temperature due to heat conduction, as can be seen during the hottest day. Similar results have been reported by Arrigoni et al. (2008) in exposed gravels and cobbles of a gravelbed river and a sandy desert stream by Valett, Fisher, and Stanley (1990) who highlighted the importance of this increased temperature in microbial processing rates recorded in the streambed. Increased streambed temperatures and the build-up of fine sediments at locations around wood are likely to result in increased sediment respiration, and potentially, an increase in greenhouse gas production, as reported by Comer-Warner et al. (2018). This increase in streambed temperature was not observed at TL3 due to the more restricted accumulation of sediment at LW1.

Model-based findings of Hester et al. (2009) and Menichino and Hester (2014) have shown that the introduction of instream structures, representative of generalized weir/wood jam/cross vein structures resulted in enhanced spatial and temporal variability in streambed temperatures. They found that in addition to increasing HEF, the occurrence of sediments with low hydraulic conductivity, such as those locations of sediment deposition around wood played an important a role in increasing the cooling and buffering of temperatures along the HEF due to increased hyporheic residence time resulting from instream structures. However, our results show that the streambed around wood structures had a more extreme temperature range. Due to the dynamic nature of the fine, sandy streambed found at the Hammer Stream, the sediments around instream wood were prevented from consolidating and forming areas of lower hydraulic conductivity which would contribute to heat buffering. Additionally, this lack of low conductivity sediments results in the creation of short, rather than long hyporheic exchange pathways, as evidenced by the strong surface water influence found around wood.

The provision of thermal refugia in the hyporheic zone remains an active research area (e.g., Faulkner, Brooks, Keenan, & Forshay, 2020; Folegot, Krause, Mons, Hannah, & Datry, 2018; Stubbington, 2012; Vander Vorste, Mermillod-Blondin, Hervant, Mons, & Datry, 2017; Wood et al., 2010), with predicted climate change impacts, including reduced river flow twinned with increased air and subsequently river temperatures highlighting the future relevance of such habitats (Folegot et al., 2018; Pyne & Poff, 2017). Previous research conducted in upland and headwater streams have found that instream wood drives the provision of thermal refugia to instream biota (Poole & Berman, 2001a), including invertebrates (Johnson, Breneman, & Richards, 2003; Sawyer & Cardenas, 2012), fish (Baxter & Hauer, 2000; Ebersole, Liss, & Frissell, 2003) and microbes (Poole et al., 2008). In comparison, our results from a small lowland sand bed stream show that rather than providing thermal buffering to the streambed (colder temperatures in summer, warmer temperatures in winter), the wood increased the seasonal temperature extremes (increased summer and decreased winter temperatures) at shallow depths by enhancing infiltration of warmer (summer) and colder (winter) surface water. This relative difference in seasonal surface water temperature is due to the slower flow and more open nature of the vegetation canopy at lowland river sites, which result in more extreme surface water temperatures than those experienced at upland sites (Garner, Malcolm, Sadler, & Hannah, 2017).

This loss of temperature buffering and hyporheic refugia has the potential to have either negative or positive effects on streambed dwelling biota. Aquatic insects and cold-water fish species generally have an optimal thermal regime which determines the success, rate and duration of larval growth and development and adult survival (Burkholder et al., 2008; Malcolm et al., 2004; Vannote & Sweeney, 1980). In these cases, the promotion of more extreme streambed temperatures and loss of thermal refugia is likely to negatively impact these species. Previous research by Magliozzi, Usseglio-Polatera, Meyer, and Grabowski (2019) on the Hammer Stream reported that locations associated with wood structures typically contained hyporheic invertebrates associated with temporal instability and flow disturbance in comparison to control sites without wood, suggesting that the dynamic (geomorphic, hydraulic and thermal) conditions present near the wood altered the benthic community.

Other streambed biota may not be as adversely impacted by seasonal temperature extremes. For example, work by Silva and Williams (2005) has shown that hyporheic microbial richness was positively correlated with temperature and vertical hydraulic gradient, whereby alteration of streambed temperatures due to HEF manipulation led to an increase in the growth of nitrifying bacteria which were normally less dominant in the streambed. Streambed microbial activity was also found to respond to diel temperature fluctuations, with a peak in activity when sediment temperatures were the highest (Claret & Boulton, 2003). These results, therefore, suggest that the observed variability in streambed temperatures around wood structures and in particular downstream of wood are likely to influence microbial communities and their subsequent activity which benefit from the improved spatio-temporal temperature diversity provided by the presence of wood. Indeed, our previous research within the Hammer Stream has shown that reach scale ecosystem respiration at baseflow conditions were highest in reaches with higher wood loading (Blaen et al., 2018), although nitrate reduction adjacent to instream wood (<1 m away) was only significantly higher at high flow events (Shelley et al., 2017). Evidence by Zheng, Cardenas, and Wang (2016) further revealed that higher streambed temperatures increased the nitrate removal efficiency of the streambed, resulting in the hyporheic zone becoming a nitrate sink rather than a source (particularly where nitrate supply is high). These results suggests that further work on the potential of wood restoration programs in attenuating high surface water nitrate levels, such as those found in lowland, agricultural areas remains. However, future reintroduction and promotion of wood in rivers should consider the local conditions and range of pressures which differently affect upland and lowland rivers to ensure that restoration efforts are designed to maximize the desired management objectives.

ACKNOWLEDGEMENTS

This work was funded by the Natural Environment Research Council (grant agreement NE/L003872/1). We thank Chris Grange, Warren Vokes, and Sylvia Folegot for field assistance, Rebwar Dara for sediment core data in Figure 1, and Mr Ferguson, Margaret Bendall, Paul Bruce and the monks of Chithurst Buddhist Monastery for land permissions and support during our field campaign. Thanks to Catherine Moody and Mark Smith for comments on early versions of the manuscript.

DATA AVAILABILITY STATEMENT

Data is available from the corresponding author (MJK) upon request

ORCID

Megan J. Klaar https://orcid.org/0000-0001-8920-4226
David M. Hannah https://orcid.org/0000-0003-1714-1240

REFERENCES

Acuna, V., Wolf, A., Uehlinger, U., & Tockner, K. (2008). Temperature dependence of stream benthic respiration in an alpine river network under global warming. *Freshwater Biology*, *53*, 2076–2088.

Arrigoni, A., Poole, G. C., Mertes, L. A., O'daniel, S. J., Woessner, W. W., & Thomas, S. A. (2008). Buffered, lagged or cooled? Disentangling hyporheic influences on temperature cycles in stream channels. *Water Resources Research*, *44*, W09418.

Ashcroft, M. B. (2010). Identifying refugia from climate change. *Journal of Biogeography*, *37*, 1407–1413.

Baxter, C. V., & Hauer, F. R. (2000). Geomorphology, hyporheic exchange, and selection of spawning habitat by bull trout (*Salvelinus confluentus*). *Canadian Journal of Fisheries and Aquatic Sciences*, *57*, 1470–1481.

Blaen, P. J., Kurz, M. J., Drummond, J. D., Knapp, J. L. A., Mendoza-Lera, C., Scmadel, N. M., … Krause, S. (2018). Woody debris is related to reach-scale hotspots of lowland stream ecosystem respiration under baseflow conditions. *Ecohydrology*, *11*, e1952.

Bocchiola, D. (2011). Hydraulic characteristics and habitat suitability in presence of woody debris: A flume experiment. *Advances in Water Resources*, *34*, 1304–1319.

Boulton, A. J. (2007). Hyporheic rehabilitation in rivers: Restoring vertical connectivity. *Freshwater Biology*, *52*, 632–650.

Burkholder, B. K., Grant, G. E., Haggerty, R., Khangaonkar, T., & Wampler, P. J. (2008). Influence of hyporheic flow and geomorphology on temperature of a large, gravel-bed river, Clackamas River, Oregon, USA. *Hydrological Processes*, *22*, 941–953.

Caissie, D. (2006). The thermal regime of rivers: A review. *Freshwater Biology*, *51*, 1389–1406.

Claret, C., & Boulton, A. J. (2003). Diel variation in surface and subsurface microbial activity along a gradient of drying in an Australian sand-bed stream. *Freshwater Biology*, *48*, 1739–1755.

Coe, R. (2002). *It's the effect size, stupid. What effect size is and why its important*. Paper presented at Annual Conference of the British Educational Research Association, Exeter: Devon. Education-line, 18.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (Second ed.) New Jersey, NJ: Lawrence Erlbaum Associates.

Comer-Warner, S. A., Romeijn, P., Gooddy, D. C., Ullah, S., Kettridge, N., Marchant, B., … Krause, S. (2018). Thermal sensitivity of CO_2 and CH_4 emissions varies with streambed sediment properties. *Nature Communications*, *9*, 2803.

Daniels, M. D. (2006). Distribution and dynamics of large woody debris and organic amtter in a low-energy meandering stream. *Geomorphology*, *77*, 286–298.

Dara, R. N. (2017). *Using ground penetrating radar (GPR) for identifying floodplan and riverbed structural heterogeneity and implications for groundwater-surface water exchange*. PhD, University of Birmingham.

Ebersole, J. L., Liss, W. J., & Frissell, C. A. (2003). Thermal heterogeneity, stream channel morphology, and salmonid abundance in northeastern Oregon streams. *Canadian Journal of Fisheries and Aquatic Sciences*, *60*, 1266–1280.

England, J., Dobbek, L., Leeming, B. F., Gurnell, A. M., & Wharton, G. (2019). Restoration of a chalk stream using wood: Assessment of habitat improvements using the Modular River Survey. *Water and Environment Journal*, *0*, 1–12.

Faulkner, B. R., Brooks, J. R., Keenan, D. M., & Forshay, K. J. (2020). Temperature decrease along hyporheic pathlines in a large river riparian zone. *Ecohydrology*, *13*, e2160.

Folegot, S., Krause, S., Mons, R., Hannah, D., & Datry, T. (2018). Mesocosm experiments reveal the direction of groundwater- surface water exchange alters the hyporheic refuge capacity under warming scenarios. *Freshwater Biology*, *63*, 165–177.

Foster, I. D. L., Biddulph, M., Boardman, J., Copeland-Phillips, R., Rvans, J., Pulley, S. J., … Collins, A. L. (2019). A paleoenvironmental study of particle size-specific connectivity - New insights and implications from the West Sussex Rother Catchment, United Kingdom. *River Research and Applications*, *35*(8), 1192–1202.

Fryirs, K., & Brierley, A. (2016). Assessing the geomorphic recovery of rivers: Forecasting future trajectories of adjustment for use in management. *WIREs Water*, *3*, 727–748.

Garner, G., Malcolm, I. A., Sadler, J. P., & Hannah, D. (2017). The role of riparian vegetation density, channel orientation and water velocity in determining river temperature dynamics. *Journal of Hydrology*, *553*, 471–485.

Grabowski, R. C., Gurnell, A. M., Burgess-Gamble, L., England, J., Holland, D., Klaar, M. J., … Wharton, G. (2019). The current state of the use of large wood in river restoration and management. *Water and Environment Journal*, *33*(3), 366–377.

Greer, G., Carlson, S., & Thompson, S. (2019). Evaluating definitions of salmonid thermal refugia using in situ measurements in the Eel River, Northern California. *Ecohydrology*, *12*, e2101.

Gurnell, A. M., Tockner, K., Edwards, P., & Petts, G. E. (2005). Effects of deposited wood on biocomplexity of river corridors. *Frontiers in Ecology and Environment*, *3*, 377–382.

Hannah, D., Malcolm, I. A., Soulsby, C., & Youngson, A. F. (2004). Heat exchages and temperatures within a salmon spawning stream in the Cairngorms, Scotland: Seasonal and sub-seasonal dynamics. *River Research and Applications*, *20*, 635–652.

Hannah, D. M., Malcolm, I. A., & Bradley, C. (2009). Seasonal hyporheic temperature dynamics over riffle bedforms. *Hydrological Processes*, *23*, 2178–2194.

Hartwig, M., & Borchardt, D. (2015). Alteration of key hyporheic functions through biological and physical clogging along a nutrient and fine-sediment gradient. *Ecohydrology*, *8*, 961–975.

Harvey, G. L., Henshaw, A. J., Parker, C., & Sayer, C. D. (2018). Re-introduction of structurally complex wood jams promotes channel and habitat recovery from overwidening: Implications for river conservation. *Marine and Freshwater Ecosystems*, *28*, 395–407.

Hester, E. T., Cardenas, M. B., Haggerty, R., & Apte, S. V. (2017). The importance and challenge of hyporheic mixing. *Water Resources Research*, *53*, 3565–3575.

Hester, E. T., & Doyle, M. W. (2008). In-stream geomorphic structures as drivers of hyporheic exchange. *Water Resources Research*, *44*, W03417.

Hester, E. T., Doyle, M. W., & Poole, G. C. (2009). The influence of in-stream structures on summer water temperatures via induced hyporheic exchange. *Limnology and Oceanography*, *54*, 355–367.

Hester, E. T., & Gooseff, M. N. (2010). Moving beyond the banks: Hyporheic restoration is fundamental to restoring ecological services and functions of streams. *Environmental Science and Technology*, *44*, 1521–1525.

Hester, E. T., Hammond, B., & Scott, D. T. (2016). Effects of inset floodplains and hyporheic exchange induced by in-stream structures on nitrate removal in a headwater stream. *Ecological Engineering*, *97*, 452–464.

Johnson, L. B., Breneman, D. H., & Richards, C. (2003). Macroinvertebrate community structure and function with large wood in low gradient streams. *River Research and Applications*, *19*, 199–218.

Klaar, M. J., Hill, D. F., Maddock, I., & Milner, A. M. (2011). Interactions between instream wood and hydrogeomorphic development wihtin recently deglaciated streams in Glacier Bay National Park, Alaska. *Geomorphology*, *130*, 208–220.

Krause, S., Hannah, D. M., Fleckenstein, J. H., Heppell, C. M., Kaeser, D., Pickup, R., … Wood, P. J. (2011). Inter-disciplinary perspectives on processes in the hyporheic zone. *Ecohydrology*, *4*, 481–499.

Krause, S., Klaar, M. J., Hannah, D., Mant, J., Bridgeman, J., Trimmer, M., & Manning-Jones, S. (2014). The potential of large woody debris to alter biogeochemical processes and ecosystem services in lowland rivers. *WIREs Water*, *1*, 263–275.

Lautz, L. K., & Fanelli, R. M. (2008). Seasonal biogeochemical hotspots in the streambed around restoration structures. *Biogeochemistry*, *91*, 85–104.

Lazar, J. G., Gold, A. J., Addy, K., Moyer, P. M., Forshay, K. J., & Groffman, P. M. (2014). Instream large wood: Denitrification hotspots with low N_2O production. *Journal of the American Water Resources Association*, *50*, 615–625.

Magliozzi, C., Grabowski, R. C., Packman, A. I., & Krause, S. (2018). Towards a conceptual framework of hyporheic exchange across spatial scales. *Hydrology and Earth Systems Science*, *22*, 6136–6185.

Magliozzi, C., Usseglio-Polatera, P., Meyer, A., & Grabowski, R. C. (2019). Functional traits of hyporheic and benthic invertebrates reveal importance of wood-driven geomorphical processes in rivers. *Functional Ecology*, *33*, 1758–1770.

Malcolm, I. A., Soulsby, C., & Youngson, A. F. (2002). Thermal regime in the hyporheic zone of two contrasting salmonid spawning streams. *Fisheries Management and Ecology*, *9*, 1–10.

Malcolm, I. A., Soulsby, C., Youngson, A. F., Hannah, D. M., Mclaren, I. S., & Thorne, A. (2004). Hydrological influences on hyporheic water quality: Implications for salmon survival. *Hydrological Processes*, *18*, 1543–1560.

Menichino, G. T., & Hester, E. T. (2014). Hydraulic and thermal effects of in-stream structure-induced hyporheic exchange across a range of hydraulic conductivities. *Water Resources Research*, *50*, 4643–4661.

Mutz, M. (2000). Influences of woody debris on flow patterns and channel morphology in a low energy, sand-bed stream reach. *International Reviews in Hydrobiology*, *85*, 107–121.

Mutz, M., & Rohde, A. (2003). Processes of surface-subsurface water exchange in a low energy sand-bed stream. *International Reviews in Hydrobiology*, *88*, 290–303.

Neal, C., Bowes, M., Jarvie, H. P., Scholefield, P., Leeks, G., Neal, M., … Davies, C. E. (2012). Lowland river water quality: A new UKdata resource for process and environmental management analysis. *Hydrological Processes*, *26*, 949–960.

Nimick, D. A., Gammons, C. H., & Parker, S. R. (2011). Diel biogeochemical processes and their effect on the aqueous chemistry of streams: A review. *Chemical Geology*, *283*, 3–17.

Norman, F. A., & Cardenas, M. B. (2014). Heat transport in hyporheic zones due to bedforms: An experimental study. *Water Resources Research*, *50*, 3568–3582.

Pilotto, F., Bertoncin, A., Harvey, G. L., Wharton, G., & Pusch, M. T. (2014). Diversification of stream invertebrate communities by large wood. *Freshwater Biology*, *59*, 2571–2583.

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

Poole, G. C., & Berman, C. H. (2001b). Pathways of human influence on water temperature dynamics in stream channels. *Environmental Management*, *27*(6), 787–802.

Poole, G. C., O'daniel, S. J., Jones, K. L., Woessner, W. W., Bernhardt, E. S., Helton, A. M., … Beechie, T. J. (2008). Hydrologic spiralling: The role of multiple interactive flow paths in stream ecosystems. *River Research and Applications*, *24*, 1018–1031.

Pyne, M. I., & Poff, N. L. (2017). Vulnerability of stream community composition and function to projected thermal warming and hydrologic change across ecoregions in the western United States. *Global Change Biology*, *23*, 77–93.

Roni, P., Beechie, T. J., Pess, G., & Hanson, K. (2014). Wood placement in river restoration: Fact, fiction and future direction. *Canadian Journal of Fisheries and Aquatic Sciences*, *72*, 466–478.

Sawyer, A. H., & Cardenas, M. B. (2012). Effect of experimental wood addition on hyporheic exchange and thermal dynamics in a losing meadow stream. *Water Resources Research*, *48*, W10537.

Sawyer, A. H., Cardenas, M. B., & Buttles, J. (2011). Hyporheic exchange due to channel-spanning logs. *Water Resources Research*, *47*, W08502.

Shelley, F., Klaar, M. J., Krause, S., & Trimmer, M. (2017). Enhanced hyporheic exchange flow around woody debris does not increase nitrate reduction on a sandy streambed. *Biogeochemistry*, *136*, 353–372.

Silva, L., & Williams, D. D. (2005). Exploration of riffle-scale interactions between abiotic variables and microbial assemblages in the hyporheic zone. *Canadian Journal of Fisheries and Aquatic Sciences*, *62*, 276–290.

Smith, M. W., & Vericat, D. (2015). From experimental plots to experimental landscapes: Topography, erosion and deposition in sub-humid badlands from structure-from-motion photogrammetry. *Earth Surface Processes and Landforms*, *40*, 1656–1671.

Smock, L. A., Metzler, G. M., & Gladden, J. E. (1989). Role of debris dams in the structure and functioning of low-gradient headwater streams. *Ecology*, *70*, 764–775.

Stubbington, R. (2012). The hyporheic zone as an invertebrate refuge: A review of variability in space, time, taxa and behaviour. *Marine and Freshwater Research*, *63*, 293–311.

Thompson, M. S. A., Brooks, S. J., Sayer, C. D., Woodward, G., Axmacher, J. C., Perkins, D. M., & Gray, C. (2018). Large woody debris “rewilding” rapidly restores biodiversity in riverine food webs. *Journal of Applied Ecology*, *55*, 895–904.

Valett, H. M., Fisher, S. G., & Stanley, E. H. (1990). Physical and chemical charactersitics of the hyporheic zone of a Sonoran desert stream. *Journal of the North Americal Benthological Society*, *9*, 201–215.

Vander Vorste, R., Mermillod-Blondin, F., Hervant, F., Mons, R., & Datry, T. (2017). *Gammarus pulex* (Crustacea: Amphipoda) avoids increasing water temperature and intraspecific competition through vertical migration into the hyporheic zone: A mesocosm experiment. *Aquatic Sciences*, *79*, 45–55.

Vannote, R. L., & Sweeney, B. W. (1980). Geographic analysis of thermal equilibria: A conceptual model for evaluating the effect of natural and modified thermal regimes on aquatic insect communities. *The American Naturalist*, *115*, 667–695.

Webb, B. W., Hannah, D. M., Moore, R. D., Brown, L. E., & Nobilis, F. (2008). Recent advances in stream and river temperature research. *Hydrological Processes*, *22*, 902–918.

Williams, R. D. (2012). Section 2.3.2: DEMs of difference. In S. J. Cook, L. E. Clarke, & J. M. Nield (Eds.), *Geomorphological techniques (Online Edition)*. London, UK: British Society for Geomorphology.

Wohl, E., Angermeier, P. L., Bledsoe, B. P., Kondolff, G. M., Macdonnell, L., Merritt, D. M., … Tarboton, D. (2005). River restoration. *Water Resources Research*, *41*, W10301.

Wohl, E., Lane, S. N., & Wilcox, A. C. (2015). The science and practice of river restoration. *Water Resources Research*, *51*, 5974–5997.

Wood, P. J., Boulton, A. J., Little, S., & Stubbington, R. (2010). Is the hyporheic zone a refugium for macroinvertebrates during severe low flow conditions? *Fundamental and Applied Limnology*, *176*, 377–390.

Zheng, L., Cardenas, M. B., & Wang, L. (2016). Temperature effects on nitrogen cycling and nitrate removal-production efficiency in bed form-induced hyporheic zones. *Journal of Geophysical Research: Biogeosciences*, *121*, 1086–1103.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: Klaar MJ, Shelley FS, Hannah DM, Krause S. Instream wood increases riverbed temperature variability in a lowland sandy stream. *River Res Applic*. 2020; 36:1529–1542. https://doi.org/10.1002/rra.3698