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Drought impacts on river water temperature: A process-based understanding from temperate climates

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Abstract

High river water temperature (T_w) extremes have been widely reported during drought conditions as extreme low-flows often coincide with high atmospheric energy inputs. This has significant implications for freshwater ecosystem health and sustainable river management practices globally. However, the extent to which different meteorological and hydrological processes interact during droughts to govern T_w dynamics, and how this varies between environmental contexts, remains poorly understood. Here, we review the mechanisms controlling T_w dynamics during droughts across temperate, maritime environments, using the United Kingdom as a detailed case study. We evidence that T_w spikes have widely occurred during extreme low-flow events observed within droughts, but such trends have been inconsistent due to varying hydroclimatic conditions and river basin controls. To better understand this, we re-conceptualize the mechanisms governing drought-induced T_w dynamics operating across three 'process sets': (i) 'energy flux dynamics' as non-advective controls on T_w; (ii) the role of 'reach-scale habitat conditions' in mediating non-advective controls on T_w, including hydraulic properties (e.g., residence time) and physical conditions (e.g., riparian vegetation coverages, wetted perimeters); (iii) 'water source contributions' (surface water and groundwater) as advective heat and water flow controls. We review natural and anthropogenic influences affecting T_w controls within each process set and discuss how such mechanisms are likely to change under drought conditions. More systematic research (spanning various river environments and drought severities) is required to test such concepts, with existing scientific knowledge on drought-induced T_w dynamics being largely gleaned from studies examining non-extreme low-flow conditions or with broader focuses (e.g., annual thermal dynamics). We conclude by highlighting critical future research questions that need to be answered to better model T_w dynamics during future droughts and for unmonitored sites. Such scientific advances would more effectively inform how high T_w extremes could be better managed through evidence-based mitigation and adaptation strategies.

KEYWORDS
adaptation, climate change, habitat, heatwave, low-flow, management, stream, thermal

1 | INTRODUCTION

River water temperature ('T_w' herein) is widely recognized as a 'master' water quality variable in lotic environments due to its fundamental importance for freshwater ecosystems and the societal implications associated with this (Ficklin et al., 2023; Olden & Naiman, 2010). Extreme thermal events in rivers therefore have significant ramifications for people and nature, and T_w peaks have been widely associated with drought events globally. Droughts are broadly defined as an extreme lack of water relative to 'normal' conditions, and can be characterized from meteorological, hydrological, agricultural/soil moisture, socio-economic and ecological perspectives (Sarremejane et al., 2022). Various indices exist globally that characterize the severity of drought conditions based on their magnitude, duration, frequency and/or geographic extent (Sarremejane et al., 2022). Most drought indices focus on meteorological conditions (e.g., precipitation or temperature anomalies) that typically display greater spatial transferability compared to hydrological-based metrics (White et al., 2022). Drought indices can be broadly categorized into threshold level methods or standardized indices (Sarremejane et al., 2022). Threshold level methods entail establishing a specific value for a hydrometeorological variable of interest, below which the system is considered to be in a drought (e.g., river discharge percentiles like Q95 and Q99—the discharge exceeded 95% and 99% of the time, respectively). Standardized drought indices fit a parametric distribution from accumulated hydrometeorological information (e.g., precipitation, river runoff or discharge), and statistics from the resulting standardized normal distribution are used to indicate the extent of water availability (Barker et al., 2016). Such examples include the Palmer drought severity index (PDSI), and the standardized index range characterizing deficits in precipitation (SPI), precipitation and evaporation (SPEI), streamflow (discharge—SSI) and soil moisture (SMI; Barker et al., 2016).

T_w dynamics during droughts are largely driven by atmospheric water deficits (meteorological) that reduce surface water and potentially groundwater availability (hydrological; see Figure 1). Extreme low-flow conditions can increase the sensitivity of T_w to energy heat fluxes, and solar radiative energy inputs in particular, by changing the thermal buffering capacity and habitat conditions (e.g., declining flow depths) of watercourses. Solar radiation levels exposed to river environments intensify during hot spells like heatwaves (van Vliet et al., 2011), which are defined as periods of prolonged high air temperatures (normally spanning at least three consecutive days—Beckett & Sanderson, 2022). Hot and dry meteorological conditions often co-occur due to reduced surface water volumes limiting evaporative cooling and dry soils transferring heat to the atmosphere (AghaKouchak et al., 2020). Such synergistic influences operating simultaneously has significant implications for high T_w extremes, which are increasingly likely during compound (co-occurring) drought-heatwaves (AghaKouchak et al., 2020).

High T_w extremes have been widely observed across temperate, maritime climates during droughts (and compound drought-heatwaves), and the magnitude of such thermal increases are estimated to

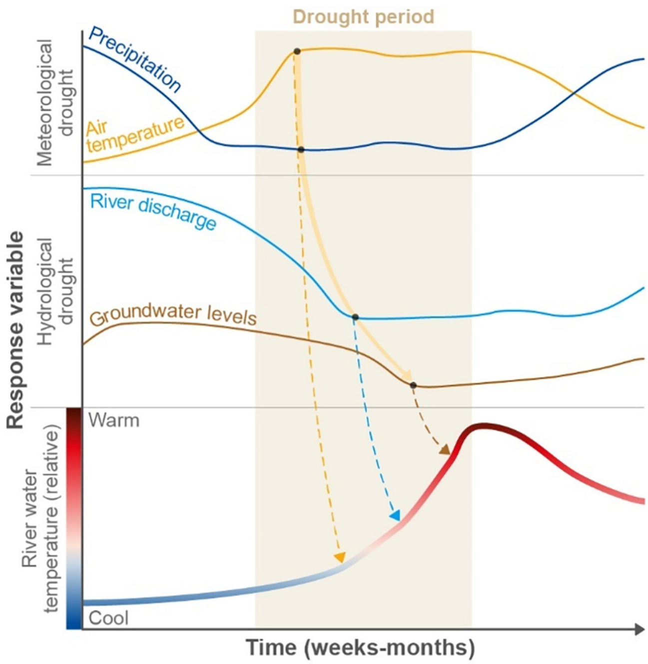

FIGURE 1 A conceptual diagram indicating river water temperature (T_w) responses to meteorological and hydrological drought propagation.

increase with climate change at rates comparable to drier and warmer (e.g., arid) environments worldwide (van Vliet et al., 2011, 2013). In this review, we synthesize evidence on the mechanisms governing T_w dynamics during droughts in temperate, maritime environments ('Cfb' under the Köppen climate classification). For this, we use the United Kingdom (UK) as a detailed case study of impacts, which has hosted fundamental research advancing our global scientific understanding of T_w controls and dynamics (Hannah & Garner, 2015). Moreover, various information sources and publications (e.g., Barker et al., 2019; Turner et al., 2021; UK Centre for Ecology and Hydrology, n.d.) can help reliably identify drought conditions, thus providing greater hydroclimatic context to T_w studies with broader research focuses (e.g., annual thermal dynamics). We primarily focus on evidence from summer months (June–August), where dry and warm meteorological conditions and low-flow conditions are most likely to occur. While prioritizing summer conditions provides greater focus and more reliable comparisons between studies for this review, we acknowledge that both non-summer droughts and wet summer conditions (e.g., summer storm surges) can also have major implications for T_w (Wilby, Johnson, et al., 2015). This review primarily synthesizes evidence from rural, upland river environments, which has been the focus of most UK research examining the mechanisms shaping T_w during droughts.

In this paper, we conceptualize the mechanisms governing T_w operating across three 'process sets': (i) 'energy flux dynamics' as non-advective controls on T_w; (ii) the role of 'reach-scale habitat conditions' in mediating non-advective controls on T_w, including hydraulic (e.g., residence time) and physical conditions (e.g., riparian vegetation coverages, wetted perimeters); and (iii) 'water source contributions' (surface water and groundwater) as advective heat and water flow controls (such heat inputs from precipitation are not considered here due to their limited influence on T_w dynamics—e.g., Webb & Zhang, 1997). We then review how different human influences (pressures and management activities) modify key mechanisms operating across the three process sets. Critical research gaps are summarized across sections reviewing natural and anthropogenic controls on drought-induced T_w dynamics. We later highlight how a better process-based understanding can underpin more robust and accurate models predicting T_w dynamics during future droughts and at unmonitored sites, which can inform evidence-based management and adaptation efforts.

2 | RIVER WATER TEMPERATURE DYNAMICS DURING UK DROUGHTS

Hot and dry climatic conditions in UK (and other countries in western Europe) are typically driven by easterly winds from continental climates and/or high pressure systems, which have instigated various nationally iconic ('benchmark') droughts throughout the last century. Notable benchmark UK droughts include 1975–1976, 1983–1984, 1988–1992, 2003, 2004–2006, 2010–2012, 2018–2019 and 2022 (Barker et al., 2019; UK Centre for Ecology and Hydrology, 2022; Turner et al., 2021), and are the focus of many of the UK studies synthesized in this review. Wilby, Prudhomme, et al. (2015) noted the longest period of below-average river discharges in the UK spanned 5.5 years between 1988 and 1993, although extreme low-flow conditions within droughts often last weeks to months and typically occur during summer months (White et al., 2022). Heatwaves within droughts typically span even shorter timeframes, with a maximum duration of 15-days being reported in the UK during 1976 and 2018 (Beckett & Sanderson, 2022). The occurrence of hot and dry summers has increased drought intensities over recent decades (Barker et al., 2019) and the 'United Kingdom Climate Projections' (UKCP18; Lowe et al., 2019) indicate these trends will continue with average summer air temperature increases of 0.9–5.4°C by 2070 (high emission scenario). The same UKCP18 climate model experiment outputs indicate corresponding precipitation levels are likely to change between −47% to 2%.

Here, we present evidence indicating a strong association between T_w values and various benchmark UK droughts, but also highlight notable inconsistencies. Table 1 displays various studies reporting T_w increases during droughts, most notably during the iconic 1975–1976 event (principally in the latter year when hydrometeorological conditions were most intense) that impacted large parts of western Europe and caused high T_w internationally (Van Vliet et al., 2011). However, in southwest England, Webb and Walling (1993) found that although maximum annual T_w was high during 1976 (20.6°C), this was greater during the 1983 drought (22.3°C) due to higher air temperatures (and associated solar radiative forcings—see below). Elliott (2000) reported T_w values of up to 29°C during 1976, which was the highest thermal extreme identified in this literature review search, although temperatures of >30°C have been observed in England (Environment Agency, 2023) and Scotland (Jackson et al., 2021) during droughts in 2018 and 2022. Although some studies have reported substantial T_w differences between drought versus non-drought years (Table 1), others have reported only modest or negligible changes (e.g., Garner et al., 2015; Hutchins et al., 2016).

Long-term (1974–2022) T_w spot-sample observations and accompanying extreme low-flow conditions from for four lowland rivers are presented in Figure 2 (for more details, see Supporting Information, Appendix S1). This highlights high T_w values and extreme low-flows occurring during the 1975–1976 drought, while T_w spikes were also observed during other benchmark droughts in 1989, 1995, 2006 and 2018. However, these trends were inconsistent, such as modest thermal peaks occurring during the 2006 and 2018 droughts in the Rivers Mersey (northwest England) and Thames (southeast England; Figures 2b,d). Additionally, high T_w extremes were not observed during the 2022 drought in rivers in northwest England (Figure 2b,c), which is likely due to water deficits being less severe than other parts of the country (UK Centre for Ecology and Hydrology, 2022).

3 | PROCESSES GOVERNING DROUGHT-INDUCED RIVER WATER TEMPERATURE: A CONCEPTUAL FRAMEWORK

3.1 | Controls shaping drought-induced river water temperature

In the following three subsections, we synthesize literature examining the key drivers of drought-induced T_w dynamics corresponding to the 'energy flux dynamics', 'reach-scale habitat conditions' and 'water source contributions' process sets. We layer human influences on these 'natural' drivers in the following section. Table 2 summarizes findings from key publications examining the mechanisms governing T_w dynamics during drought and non-drought summer periods in the UK. Studies solely focussing on the association between air temperature (used as a proxy for net heat flux) and T_w dynamics have been excluded in Table 2 as such trends do not directly capture the effects of the underlying processes (but we acknowledge such research has significantly advanced our scientific understanding of T_w responses to meteorological forcings and climatic changes - e.g., Wilby & Johnson, 2020).

Most studies examining energy flux influences on T_w have largely stemmed from studies with broader research focuses (e.g., annual thermal dynamics). Furthermore, in the UK there has been a marked spatial bias of such studies towards northeast Scotland and southwest England (Figure 3) due to research institutional specialisms. Reach-scale habitat influences on T_w have predominantly examined the effects of riparian vegetation, with a particular focus of this in central Wales where logging and clear-felling practices have been widely implemented (Stott & Marks, 2000). However, the effects of other controls like hydraulic geometries (e.g., width: depth ratios) and

TABLE 1 Various UK studies documenting water temperature (T_w) in rivers during droughts.

Drought event[a]	Location	T_w variable	T_w responses	References
1975–1976	Herefordshire, southwest England	Maximum annual T_w	27.6 and 4.6°C higher than non-drought year (1975)	Brooker et al. (1977)
	Plynlimon, central Wales.	Mean monthly T_w	~14–18°C, approximately 2–4°C higher than non-drought years (1977–1978)	Cowx et al. (1987)
	Dorset, southwest England	Maximum annual T_w	23.7 and 6.2°C higher than non-drought years (1962–1968)	Crisp et al. (1982)
	Cumbria, northwest England	Summer (1st–14th July) maximum T_w	24–29°C, 6–11°C higher than non-drought conditions in 1977 (18°C).	Elliott (2000)
	Aberdeenshire, northeast Scotland	Maximum monthly averaged T_w	~15°C, approximately 1°C higher than non-drought years (between 1970 and 2000).	Langan et al. (2001)
	Devon, southwest England	Maximum annual T_w	20.6 and 1.4°C higher than long-term average.	Webb and Walling (1993)
1983–1984	Cumbria, northwest England	Summer (1st–14th July) maximum T_w	23.5–28°C, 6.5–12°C higher than non-drought conditions in 1985 (16–17°C).	Elliott (2000)
	Devon, southwest England	Maximum annual T_w	20.0–22.3°C, 0.8–3.1°C higher than long-term average.	Webb and Walling (1993)
1989–1992	Devon, southwest England	Maximum annual T_w	21.1°C, 1.9°C higher than long-term average.	Webb and Walling (1993)
	Aberdeenshire, northeast Scotland	Maximum monthly averaged T_w	~15–17°C, approximately 1–3°C higher than non-drought years between 1970 and 2000.	Langan et al. (2001)
	Plynlimon, central Wales	Maximum monthly averaged T_w	~12–14°C in 1991–1992, approximately 2–3°C higher than non-drought year (1993).	Crisp (1997)
	Plynlimon, central Wales	Summer (mid-morning) maximum T_w	~23°C in 1989, approximately up to 5–11°C higher than non-drought years (1985–1988; the 1990 drought was ~18°C).	Neal et al. (1992)
1995	Aberdeenshire, northeast Scotland	Maximum monthly averaged T_w	~14°C, in keeping with values during non-drought years (between 1970 and 2000).	Langan et al. (2001)
	Dorset, southwest England	Maximum annual T_w	~20°C, approximately 1.5°C higher than non-drought years (1993–1994 and 1995)	Bowes et al. (2011)
2003, 2004–2006	Dumfries and Galloway, southwest Scotland	Maximum monthly averaged T_w	~18°C during 2003 open sites, approximately 2°C higher than non-drought years (2000–2002). No discernible T_w differences between years in shaded reaches.	Webb and Crisp (2006)
	Aberdeenshire, northeast Scotland	Monthly averaged T_w	~12–15°C during 2003–2005, no discernible differences with non-drought years (2007–2009), although 2006 was approximately 2–4°C warmer than long-term averages.	Garner et al. (2015)
	Hampshire, southern England	Maximum monthly T_w	~20–22°C in 2006, >2–3°C higher than other years examined (2005 – drought) and (2007 – non-drought).	Broadmeadow et al. (2011)
2010–2011	Oxfordshire, Central England	Maximum annual T_w	~20–22°C, no discernible differences with non-drought years (2009 and 2012).	Hutchins et al. (2016)
2018	Aberdeenshire, northeast Scotland	Maximum annual T_w	~17°C, approximately 3°C higher than non-drought year (2019).	Fennell et al. (2020)
	East Anglia, eastern England	Maximum annual T_w	~18°C, no discernible differences with non-drought years (between 2012 and2017).	Cooper et al. (2020)

[a]Nationally iconic, 'benchmark' drought years identified from (Barker et al., 2019; Turner et al., 2021; UK Centre for Ecology and Hydrology, 2022).

stream velocities (and residence times) on T_w have received less research attention, with most of such influences being incorporated in 'process-based' hydraulic and T_w models (see 'Modelling river water temperature under drought'; Dugdale et al., 2017) rather than within empirical observations. Limited studies have examined the effects of water source contributions and advected heat during drought

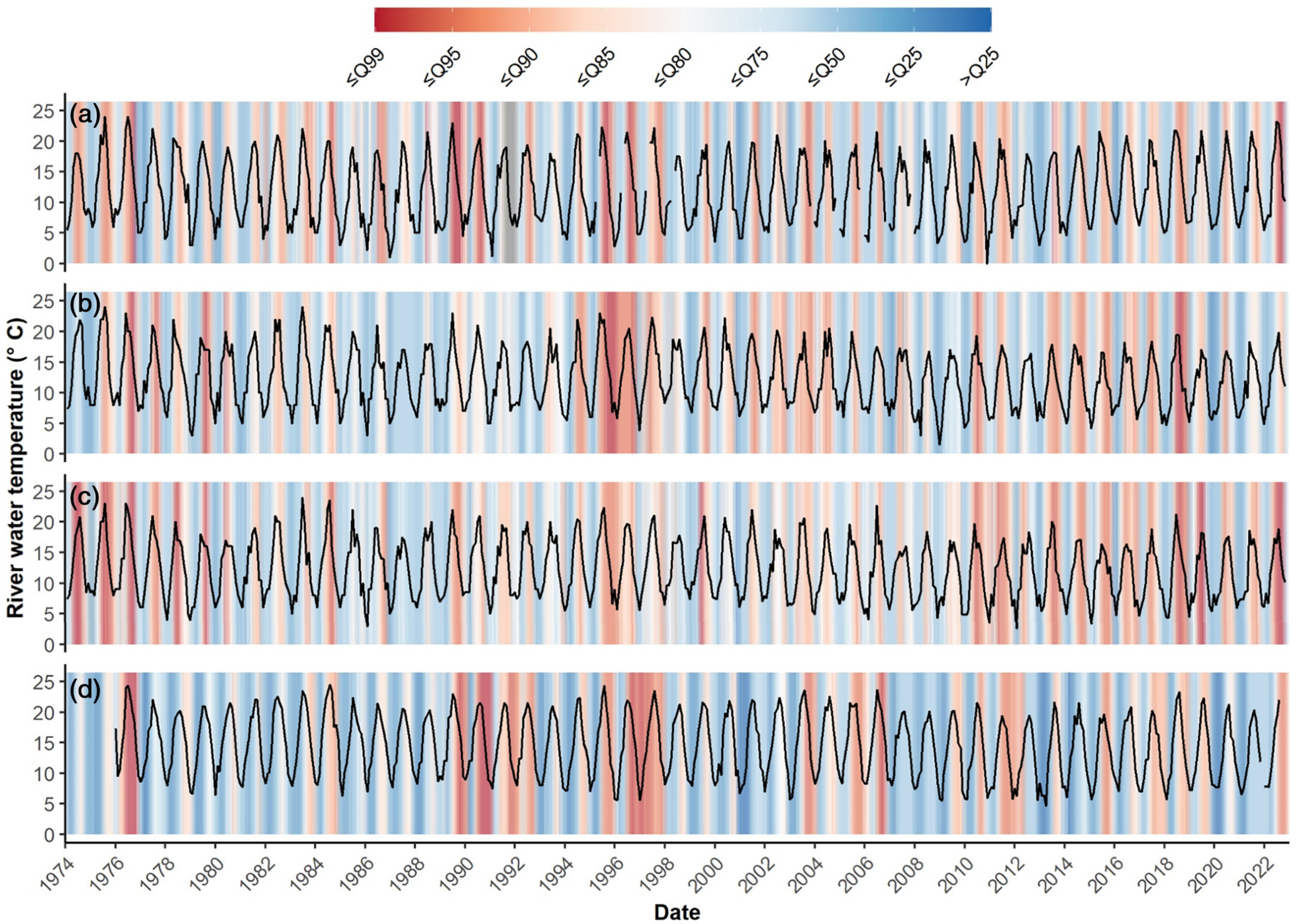

FIGURE 2 Long-term, maximum monthly river water temperature (T_w) variations across four lowland rivers in England. Shading reflects monthly minimum river discharge magnitude categories based on percentile thresholds (e.g., '≤Q99' reflecting discharges lower than that exceeded 99% of the time; '≤Q95' depicting discharges in the interval >Q99 to ≤Q95, and so on for the remaining intervals). (a) River Ouse, Yorkshire (northeast England); (b) River Mersey, Greater Manchester (northwest England); (c) River Irwell, Greater Manchester (northwest England); and (d) River Thames, London (southeast England). See Supporting Information, Appendix S1 for further details.

conditions, reinforcing the perspectives of Leach et al. (2023) based on global T_w research.

3.2 | Energy flux influences on river water temperature during drought

Although positive associations have been demonstrated between thermal energy inputs and T_w (e.g., Garner et al., 2014; Webb & Zhang, 2004), this has not been widely explored during drought periods. Various energy budget studies have presented monthly summaries of non-advective influences on T_w (e.g., Garner et al., 2015; Webb & Zhang, 1997, 2004). However, these longer time periods are typically misaligned with the shorter time periods associated with extreme low-flows or compound drought-heatwaves. Energy gains elevating T_w in river environments include incident shortwave (solar) and downward longwave (atmospheric) radiation, condensation, and in-channel friction. Predominant summer energy losses cooling rivers include longwave radiation emissions and evaporation (latent heat) effects, while sensible heat transfers (i.e., conduction at the air-water interface and convection) and water column-riverbed exchanges can have warming or cooling influences (Hannah & Garner, 2015; Leach et al., 2023).

Thermal energy budget studies spanning various river environments (Garner et al., 2015; Wawrzyniak et al., 2017; Webb & Zhang, 2004) across Cfb climates and worldwide (Leach et al., 2023) have consistently identified shortwave radiation as the primary heat input elevating T_w. Such inputs often contribute >90% of the warming effects during summer and specifically drought conditions (see Table 2) and typically outweigh any non-advective cooling influences. However, shortwave radiation can become less influential in groundwater-dominated systems and/or reaches shaded by dense riparian cover (Kaandorp et al., 2019) or by valley sides in incised systems.

Sensible heat inputs are contingent upon air temperature exceeding T_w, whereby warmer air can allow heat to be conducted into the

TABLE 2 A summary of UK studies examining mechanisms governing river water temperature (T_w) dynamics during summer drought or seasonally typical low-flow conditions. References are organized first by drought versus non-drought studies, second by process sets and then by the alphabetical order of the author's surname.

	Contextual information					T_w controls		T_w responses			
	Low-flow period[a]	Catchment position	SW/GW dominance	Dam influences	Riparian shading	Mechanism examined	Key properties	Variable	Effect	Response	References
Drought studies											
Energy flux dynamics	Drought conditions experimentally mimicked	Headwaters	GW	Free flowing	Low (potential shading from flume walls)	Solar radiation	Daily averages on a clear day were 2.4–5.5 × higher than overcast days.	Percentage contribution to total heat budget	Warming	Contributed 64% to T_w variations in daytime hours	Folegot et al. (2018)
	Compound drought-heatwave period monitored (July 2013)	Headwaters	SW	Free flowing	Mixed	Various energy fluxes	Shortwave radiation dominated heat inputs and were ~3× higher than an overcast day.	Maximum longitudinal T_w difference (1.5 km reach)	Warming	2.5°C on days with clear skies, but 0.6°C on overcast day.	Garner et al. (2014)
	Drought year (1992)	Headwaters and lowlands	Mixed	Free flowing and regulated	Mixed	Various energy fluxes	Solar radiation dominated total energy inputs, followed by sensible heat (mean contributions = 68.7% and 21.2%, respectively).	N/A	N/A	N/A	Webb and Zhang (1997)
	Drought year (1995)	Headwaters and lowlands	Mixed	Free flowing and regulated	Mixed	Various energy fluxes	Shortwave radiation dominated heat inputs, followed by sensible heat (mean contributions = 48.4%–84.9% and 5.1%–40.8%, respectively).	Monthly mean T_w	Warming	Positive effects, but this was more variable in shaded and regulated reaches.	Webb and Zhang (2004)
	Drought (2005–2006) and non-drought (2007) years	Headwaters	SW	Free flowing	Mixed	Riparian shading	Reaches spanning covered to open riparian influences were compared.	Maximum summer T_w	Cooling	Increases during drought were lower in shaded (0.1–1.7°C) versus open (0.8–3.4°C) reaches	Broadmeadow et al. (2011)
	Drought (1995) and non-drought years (1991 and 1993).	Headwaters	SW	Free flowing	Mixed	Riparian shading	Reaches with cleared and intact riparian coverages were compared.	Maximum summer T_w	Cooling	~1°C lower in shaded versus cleared reaches across both drought and non-drought years	Crisp (1997)

TABLE 2 (Continued)

	Contextual information					T_w controls		T_w responses			
	Low-flow period[a]	Catchment position	SW/GW dominance	Dam influences	Riparian shading	Mechanism examined	Key properties	Variable	Effect	Response	References
	Drought conditions mimicked	Headwaters	GW	Free flowing	Low (potential shading from flume walls)	Flow depth	Spanned 7–25 cm reflecting drought to non-drought hydrological gradients.	Maximum longitudinal T_w difference (15 m long flumes)	Warming	>3°C in drought treatments, which were ~2°C higher than non-drought treatments.	Folegot et al. (2018)
Reach-scale habitat conditions	Drought (2003–2006) and non-drought years (2007–2009)	Headwaters	Mixed	Free flowing	Mixed	Various energy fluxes; Riparian shading	Shortwave radiation dominated heat inputs, but were almost 3× lower in shaded versus open reaches.	Monthly mean T_w	Cooling	1.1°C lower in shaded versus open reaches, the former was typically cooler.	Garner et al. (2015)
	Drought (1984, 1989–1990) and non-drought years (1985–1988)	Headwaters	Mixed	Free flowing	Mixed	Riparian shading	Reaches with cleared and intact riparian coverages were compared.	Maximum summer T_w	Cooling	~4–9°C lower in shaded versus cleared reaches, and differences were most pronounced during drought years	Neal et al. (1992)
	Drought (1995) and non-drought year (1996).	Headwaters	SW	Free flowing	Mixed	Riparian shading	Riparian coverages were cleared between the two summers.	Summer (July–August) monthly maximum T_w	Cooling	5.3–7.0°C cooler pre (shaded) versus post (open) clearance, despite the former occurring during a drought.	Stott and Marks (2000)
	Drought (2003) and non-drought years (2000–2002)	Headwaters	SW	Free flowing	Mixed	Riparian shading	Reaches spanning covered to open riparian influences were compared.	Summer monthly mean maximum T_w	Cooling	~5°C lower in shaded versus open reaches, and differences were higher during drought versus non-drought years (~3–4 and 5°C, respectively).	Webb and Crisp (2006)
Water source contributions	Drought year (2018)	Headwaters	GW	Free flowing and regulated	Unclear	Deep (≥1.5 m) groundwater contributions	Sustained 65–100% of river discharges	Range of summer T_w values	Cooling	Inputs remained cool (~6–7°C) throughout the drought.	Fennell et al. (2020)

(Continues)

TABLE 2 (Continued)

	Contextual information					T_w controls		T_w responses			
	Low-flow period[a]	Catchment position	SW/GW dominance	Dam influences	Riparian shading	Mechanism examined	Key properties	Variable	Effect	Response	References
	Drought year (1992)	Headwaters and lowlands	Mixed	Free flowing and regulated	Mixed	Groundwater contributions	Groundwater exerted negative and positive contributions to the total energy budget (spanning −13.8% to 12.8%).	N/A	N/A	N/A	Webb and Zhang (1997)
Non-drought studies											
Energy flux dynamics	Non-drought year (1994)	Headwaters	Mixed	Regulated	Low	Various energy fluxes	Shortwave radiation dominated heat inputs (97.2%–98.8%), almost 2× higher than an overcast day.	Summer T_w (15-min recordings)	Warming	Positive effects that were strongest on the hottest summer day, explaining 86% ($r = 0.93$) of T_w variations.	Evans et al. (1998)
	Study period spanned 1984–2007, but droughts not assessed directly.	Headwaters and lowlands	Mixed	Unclear	Mixed	Solar radiation	Shortwave radiative inputs yielded positive effects on T_w (but air temperature effects were much higher).	Summer averaged T_w	Warming	Shortwave radiation effects were consistently low across T_w values spanning 15–20°C.	Laizé et al. (2017)
	Non-drought year (1994)	Headwaters	GW	Free flowing	Low	Various energy fluxes	Shortwave radiation dominated heat inputs.	N/A	N/A	N/A	Webb and Zhang (1999)
Reach-scale habitat conditions	Non-drought year (2010)	Headwaters	GW	Free flowing	Mixed	Various energy fluxes; Riparian shading	Shortwave radiation dominated heat inputs (96.2%–97.5%), and were ~2–3× lower in shaded versus open sites.	Summer maximum T_w	Cooling	2°C cooler in shaded versus open reaches.	Dugdale et al. (2018)
	Non-drought year (2004)	Headwaters	Mixed	Free flowing	Mixed	Various energy fluxes; Riparian shading	Shortwave radiation dominated heat inputs (95.9%–100%), and were almost 5× lower in shaded versus open sites.	Summer (August) maximum T_w	Cooling	0.5°C cooler in shaded versus open reaches.	Hannah et al. (2008)

TABLE 2 (Continued)

	Contextual information					T_w controls		T_w responses			
	Low-flow period[a]	Catchment position	SW/GW dominance	Dam influences	Riparian shading	Mechanism examined	Key properties	Variable	Effect	Response	References
	Non-drought year (2008; 'hottest week')	Headwaters and lowlands	Mixed	Free flowing	Mixed	Riparian shading	Modelled reforestation that covered 100% of the river network	Mean weekly maximum T_w	Cooling	1.1°C cooler compared to measured land cover	Hrachowitz et al. (2010)
	Non-drought year (2015)	Headwaters and lowlands	Mixed	Free flowing (largely)	Mixed	Channel width	Spatial models incorporated widths from 1 to over 100 m	Maximum summer T_w	Warming	Almost linear positive relationship modelled	Jackson et al. (2017)
	Non-drought year (2015)	Headwaters and lowlands	Mixed	Free flowing and regulated	Mixed	Riparian shading	Spatial models simulating 0%–100% riparian coverages	Maximum summer T_w	Cooling	Up to 2.8°C, cooling effects were highest when air temperatures peaked.	Jackson et al. (2018)
	Non-drought years (2011–2014)	Headwaters and lowlands	GW	Free flowing	Mixed	Solar radiation; Riparian shading	Statistical models simulating planting initiatives identified incoming solar radiation could be reduced by 30%–40%.	Maximum summer T_w	Cooling	1°C reductions with ~0.5 (headwater) and 1.1 km (lowland) of complete shade.	Johnson and Wilby (2015)
	Non-drought year (1986)	Headwaters	SW	Free flowing	Mixed	Riparian shading	Reaches spanning covered to open riparian influences were compared	Maximum summer T_w	Cooling	~0.5–2°C reductions in forested versus open sites	Weatherley and Ormerod (1990)
Water source contributions	Non-drought year (2008; 'hottest week' typical for summer)	Headwaters and lowlands	Mixed	Free flowing	Mixed	Tributary inputs	Modelled catchment-wide, spatially continuous T_w measurements	Mean weekly maximum T_w	Neutral	Mainstem (19–20°C) was buffered from warm upland (23.7°C) and cool (15.8°C) coastal tributary inputs.	Hrachowitz et al. (2010)
	Non-drought year (2015)	Headwaters and lowlands	Mixed	Free flowing and regulated	Mixed	Upstream advective inputs	Spatial models incorporating 'River Network Smoother' indicating spatial autocorrelation	Maximum summer T_w	Variable	Warmer and cooler influences in the headwaters and mid-sections of the catchment, respectively	Jackson et al. (2017), see also Jackson et al. (2018)

(Continues)

TABLE 2 (Continued)

	Contextual information					T_w controls		T_w responses			
	Low-flow period[a]	Catchment position	SW/GW dominance	Dam influences	Riparian shading	Mechanism examined	Key properties	Variable	Effect	Response	References
	Non-drought years (2011–2014)	Headwaters and lowlands	GW	Free flowing	Mixed	Upstream advective inputs	Spatial autocorrelation tested between T_w loggers	Daily maximum T_w	Variable	Positive relationship, with correlations (r) spanning 0.90–0.98.	Johnson et al. (2014), Johnson and Wilby (2015)
	Non-drought years (2011–2014)	Headwaters and lowlands	GW	Free flowing	Mixed	Groundwater contributions	Spring input inventory created across watercourses	Annual maximum T_w (likely during summer)	Cooling	Largely spanned 10–11.5°C, while spring inputs were predominantly between 8.5–10°C.	Johnson et al. (2014)
	Non-drought year (1994)	Headwaters	GW	Free flowing	Low	Groundwater contributions	Groundwater contributions to the average daily heat storage spanned 5.8%–12.1%.	Summer T_w (15-min recordings)	Cooling	Cool groundwater inputs dampened radiative effects, 0.30–0.34°C increases for every 1°C rise in air temperature.	Webb and Zhang (1999)

Abbreviations: GW, Groundwater; SW, Surface water.
[a]Nationally iconic, 'benchmark' drought years identified from (Barker et al., 2019; Turner et al., 2021; UK Centre for Ecology and Hydrology, 2022).

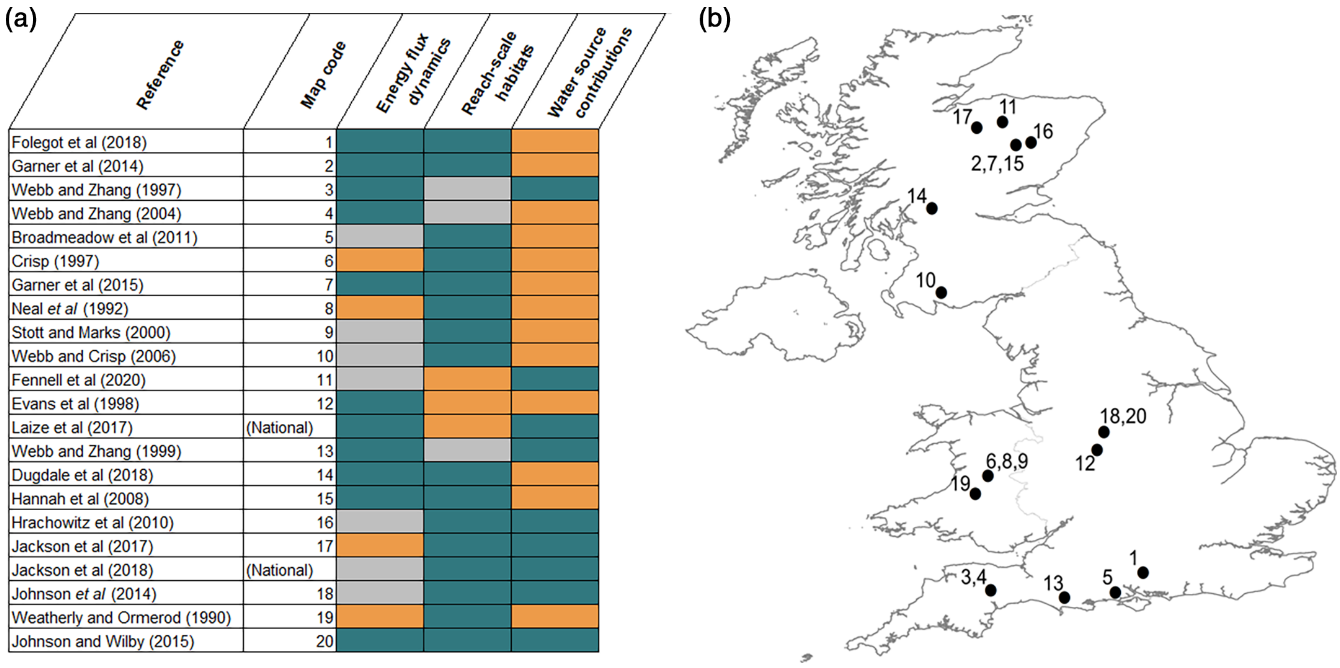

FIGURE 3 A summary of key literature examining mechanisms underpinning drought-induced river water temperature (T_w) dynamics in the UK. (a) A heatmap indicating which process sets were examined in the study (orange = not tested; grey = considered but not directly quantified; blue = empirically examined); (b) A map displaying the distribution of studies. References are ordered in the order they appear within Table 2.

water column. Sensible heat inputs often yield minimal influences on T_w, as highlighted in various studies spanning different river environments (e.g., northwest Scotland—Garner et al., 2014, 2015; central England—Evans et al., 1998; Luxembourg—Westhoff et al., 2007; France—Wawrzyniak et al., 2017). However, Kaandorp et al. (2019) quantified the importance of sensible heat on T_w in a groundwater-dominated system in the eastern region of The Netherlands due to cool subsurface inputs and warm meteorological conditions. Similarly, energy budget studies conducted on surface water dominated systems in southwest England have reported substantial sensible heat contributions comprising 70% (Webb & Zhang, 1997) and 41% (Webb & Zhang, 2004) of the non-advective heat inputs during droughts, although this was most commonly a secondary influence behind radiative influences. High sensible heat influences reported in this region potentially reflects greater air temperature–T_w differences caused by riparian shading or warm trade winds transported from the continent.

Longwave radiation typically peaks during hot and dry meteorological conditions as shortwave inputs are absorbed and emitted by the earth's surface and atmosphere, although the two are not completely congruent as the former also responds positively to cloud cover (Laizé et al., 2017). Incised and shaded streams can experience warming effects from longwave radiation during hot and dry conditions, particularly at night, whereby such energy is retained and re-emitted back towards the water surface (Kaandorp et al., 2019). However, longwave radiative fluxes most commonly exert a T_w cooling effect during the summer due to emissions from the channel, which is enhanced by warmer waters (as governed by the Stefan-Boltzmann law—Hannah et al., 2004), particularly under clear sky conditions. Various UK river energy budget studies have indicated cooling effects from longwave emissions during summer, although this was found to be less pronounced in northeast Scotland (e.g., Garner et al., 2014, 2015) compared to central (Evans et al., 1998) and southwest England (Webb & Zhang, 2004); this is likely due to denser riparian coverages and lower T_w (from being positioned at higher latitudes) in Scotland.

Condensation typically yields minor warming influences during hot and dry conditions, and latent heat exchanges during such periods are dominated by evaporative cooling effects (Dugdale et al., 2018; Webb & Zhang, 1999), as captured by 'curve flattening' effects in air temperature-T_w statistical associations (Johnson et al., 2014). Evaporative cooling effects will be higher in rivers susceptible to low atmospheric humidity and high wind speeds, including watercourses devoid of riparian zones and hence no obstructions reducing aeolian processes (Garner et al., 2015; Webb & Zhang, 1997), although how this relates to solar radiative inputs can vary significantly. For instance, in southwest England, Webb and Zhang (2004) reported that evaporative cooling influences were notably higher in reaches that were completely open or possessed limited shading, but were still lower than heat energy inputs. Garner et al. (2014) highlighted that evaporative cooling effects surpassed solar radiative inputs in one shaded reach, but comprised approximately one-third of the heat inputs in other shaded and non-shaded reaches. Critically, while it is widely recognized that evaporative cooling effects can offset thermal extremes during hot and dry conditions, how such influences respond to varying drought severities is poorly understood as most energy budget studies use empirical or semi-empirical approaches to estimate latent heat fluxes (Dugdale et al., 2017).

Bed conduction effects on T_w are driven by thermal differences between the riverbed and the overlying water column (Evans et al., 1998). This can vary depending on vertical thermal gradients in the water column, flow depth and turbidity governing the proportion of solar radiation reaching the riverbed, the absorbance/reflective properties of the benthic habitat (e.g., substrates, primary producers) and subsurface water temperature (Evans et al., 1998). While declining flow depths during droughts could increase the solar radiative forcings penetrating the riverbed, the water column typically warms at faster rates and therefore bed conduction typically yields cooling effects overall (e.g., Evans et al., 1998; Kaandorp et al., 2019; Westhoff et al., 2007). Such influences are often enhanced by cooler groundwater inputs (relative to T_w—see below). For example, Webb and Zhang (1999) reported that bed conduction contributed 71% of the total non-advective heat losses in a groundwater-dominated river during a non-drought summer; although this effect was negligible in a watercourse nearby due to dense submerged macrophyte growth that restricted water column-river bed exchanges.

Although Webb and Zhang (2004) reported friction at channel bed and banks yielded high energy inputs in two of their four studied rivers during summer (notable in a regulated system with artificially elevated low-flow discharges), various studies have reported such effects have a negligible influence on the overall heat energy budget (e.g., Evans et al., 1998; Garner et al., 2015; Kaandorp et al., 2019). Moreover, channel friction effects on T_w will typically decline during drought conditions when flow velocities and turbulence also subside (White et al., 2022).

3.3 | Reach-scale habitat influences on drought-induced river water temperature

In this sub-section, we focus on the two most widely researched reach-scale habitat conditions mediating non-advective influences on T_w: (i) riparian vegetation shading; and (ii) hydraulic geometry responses to extreme low-flow conditions.

3.3.1 | Riparian vegetation

Riparian vegetation shading on river channels is widely recognized to reduce high T_w extremes (see Table 2). However, the magnitude of such effects is dependent on complex interactions between channel width, gradient, orientation, aspect, tree height, vegetation density and characteristics, solar geometry and hydraulic properties (Garner et al., 2017; Jackson et al., 2021). While the effects of bankfull channel widths on the proportion of water shaded by riparian vegetation has been quantified in various modelling studies (Bachiller-Jareno et al., 2019; Jackson et al., 2021), this has not been widely explored with declining flow depths in drought contexts. For instance, narrower river channels (e.g., many headwater streams, lowland clay-based systems possessing cohesive banks—Sear et al., 1999) will facilitate greater shading influences. The effects of drought on riparian vegetation have received limited research, despite such extremes been widely demonstrated to cause wilting, stunted leaf growth or dieback (Ilyas et al., 2021). Moreover, critical knowledge gaps remain on wildfire effects on riparian vegetation and subsequent shading influences, which requires further research attention as such ecological threats are likely to increase with projected hydroclimatic changes (AghaKouchak et al., 2020).

Riparian vegetation reduces the incoming shortwave radiation receipt, causing shaded rivers to be cooler than comparable, but uncovered, watercourses. Webb and Zhang (2004) highlighted that shortwave radiative inputs during drought conditions were ~3–6 times higher in exposed sites relative to shaded reaches. Similarly, across Scotland, Hannah et al. (2008) and Dugdale et al. (2018) reported that shaded sites exhibited shortwave radiative inputs were between ~1–4 times lower than open reaches in non-drought summers, with T_w being between 0.5–1°C cooler. It should be noted that riparian vegetation can input heat energy into rivers by reflecting longwave radiation back towards the channel (Dugdale et al., 2018) and reducing wind speeds (thereby reducing evaporative losses—Hannah et al., 2008). However, these effects are typically outweighed by reduced shortwave radiative inputs, so that the net effect of woodland is generally to reduce temperatures during hot and dry periods relative to more exposed channels.

3.3.2 | Hydraulic geometry

River discharge is a key driver of T_w dynamics during droughts (and other hydrological conditions), not only through its effects on the thermal capacity of watercourses and shifting upstream advective inputs (see below), but also through its influence on hydraulic geometry responses to extreme low-flow conditions. Specifically, changes in the wetted widths, depths and flow velocities during droughts can strongly govern T_w by mediating the influences of non-advective controls. However, the intrinsic relationship between these three physical habitat parameters and river discharge means that disentangling their controls on T_w is scientifically challenging. This has the potential to become increasingly complex during drought conditions where 'stepped' morphological changes and disconnections (e.g., loss of lateral or longitudinal connectivity) across different low-flow severities can facilitate considerable shifts in physical habitat conditions (Sarremejane et al., 2022). Channel width influences T_w as it governs the surface area exposed to atmospheric exchanges, which is critical as most heat energy gains occur at the air-water interface and upper parts of the water column (Evans et al., 1998). Conversely, deeper waters are more protected from atmospheric energy inputs, including shortwave radiation fluxes which undergo scattering and reflection in the upper parts of the water column—an effect enhanced by enhanced high turbidity (Evans et al., 1998) or shade from macrophyte coverages (Folegot et al., 2018). Consequently, narrower and deeper channels (i.e., lower width: depth ratios) and/or morphologies that retain flow depths more effectively during extreme low-flows (e.g., 'triangular' hydraulic geometries with non-cohesive banks—sensu Ferguson, 1986) are more likely to offset high thermal extremes during droughts. The opposite applies for channels with higher width:depth ratios (i.e., wider and shallower cross-sections), which may include various groundwater-dominated river systems (Sear et al., 1999; although cooler groundwater inputs can dampen such effects—see below) or hydraulic geometries maintaining high relative wetted widths during extreme low-flow conditions, including systems with straightened (e.g., cohesive or vegetated alluvial) banks (Ferguson, 1986).

Stream velocities governed by river discharge and channel morphology (e.g., slope, width: depth ratios, bed roughness) control water residence times, which strongly influences T_w as it dictates the amount of time water is exposed to its surroundings, and thus the accumulation and dissipation of heat. For instance, Garner et al. (2017) modelled the effects of differing flow velocities on T_w dynamics along a forested reach during a compound-drought heatwave. The authors reported slow-flow conditions through a shaded system reduced maximum T_w values by 4.9°C. In The Netherlands, Kaandorp et al. (2019) reported that the enhanced residence times of a larger, instream pond elevated maximum T_w summer values by 6.4°C relative to its smaller counterpart. Hence, river systems yielding greater residence times, including those occurring along shallow gradients (e.g., lowland environments, plateau rivers) or notably widened systems (e.g., online ponds, unconfined reaches), can become more susceptible to warming during drought as they are exposed to atmospheric energy exchanges for longer periods.

3.4 | The influences of water source contribution on river water temperature during drought

How surface water and groundwater contributions shape river discharge during droughts is critical to T_w as this dictates the thermal capacity of the watercourse, whereby reduced water volumes are warmed more rapidly. For instance, Folegot et al. (2018) experimentally simulated drought conditions using outdoor flow-through flumes and reported those containing severely depleted water volumes exhibited a maximum warming of 3.3°C, ~2°C higher than those conveying higher discharges. In New Zealand, Booker and Whitehead (2022) reported that declines in river flow from the median to the fifth percentile facilitated an average T_w increased by 0.5°C, and similar findings have been reported elsewhere in Cfb climates (e.g., Van Vliet et al., 2011).

The effects of upstream advective influences (surface water contributions) on T_w is dependent on the thermal properties and relative discharges of the mainstem channel and inflowing tributaries. For instance, in northeast Scotland, Hrachowitz et al. (2010) reported that the mainstem river facilitated stable temperatures between 19 and 20°C during the hottest week in a meteorologically typical summer, which was buffered from contributions from warm (23.7°C) upland and cool (15.8°C) coastal tributaries. Conversely, Johnson et al. (2014) highlighted that tributary inputs facilitated notable longitudinal variations in T_w during a non-drought summer. Reduced advective upstream inputs becomes most prevalent when flow cessation events occur, such as systems exclusively fed by groundwater inputs (i.e., no upstream contributions—White et al., 2018) or hydrologically disconnected instream pools that undergo rapid warming (Datry, 2017).

Various studies have reported surface water contributions declining at faster rates than groundwater inputs during low-flow conditions (e.g., Dewson et al., 2007; Wawrzyniak et al., 2017; Webb & Walling, 1997). Consequently, the volume and thermal stability of groundwater inflows (or lack thereof) can have significant implications for drought-induced T_w dynamics. Groundwater inputs often cool T_w during hot and dry conditions as they are more protected from atmospheric energy influences. For instance, in a lowland system in southeast France, Wawrzyniak et al. (2017) reported that groundwater cooling effects were most influential (average reduction of 0.68°C) during a drier and warmer summer when such contributions comprised a higher proportion of the river discharge. Shallow groundwaters are often cooler than average summer air temperatures and continue declining with depth until it becomes affected by heat conducted from the Earth's core (this occurs at subsurface depths of approximately 15 m in the UK—Busby et al., 2009). For instance, in a limestone-fed headwater system in northeast Scotland, Fennell et al. (2020) reported that while T_w was highest in late July (~15°C), shallower groundwaters (≤1.2 m deep) displayed a lagged response and peaked in September (~10°C), and the temperature of deeper groundwaters (≥1.5 m deep) remained cool (~ 6–7°C) and stable throughout. How groundwater temperature varies in relation to T_w is dependent on various factors, including subsurface depths and flow rates, as well as the thermal conductivity of the lithology. For instance, some shallow groundwater inputs influenced by atmospheric energy fluxes can elevate T_w during summer (Webb & Zhang, 2004), while deeper contributions affected geothermal energy (e.g., from limestone lithologies) can also increase T_w during such periods (Johnson et al., 2014). Nevertheless, few studies have quantified groundwater influences on T_w during drought conditions (but see Fennell et al., 2020), and even less research has quantified the thermal implications of groundwater disconnections associated with extreme drought conditions.

3.5 | Re-conceptualizing mechanisms governing drought-induced river temperature dynamics

Based on the evidence synthesized above, we have conceptually detailed the dominant mechanisms that are likely to influence T_w during different drought intensities in Figure 4, which will apply to various river environments across Cfb climates and globally. Shortwave radiative inputs are likely to dominate across varying drought severities (except heavily shaded environments), while sensible heat inputs will typically exert a secondary or minimal warming influence on T_w (but will increase with air temperature). Cooling effects via longwave radiation emissions from the river surface and evaporation are likely to increase with drought severity, both driven by elevated T_w values

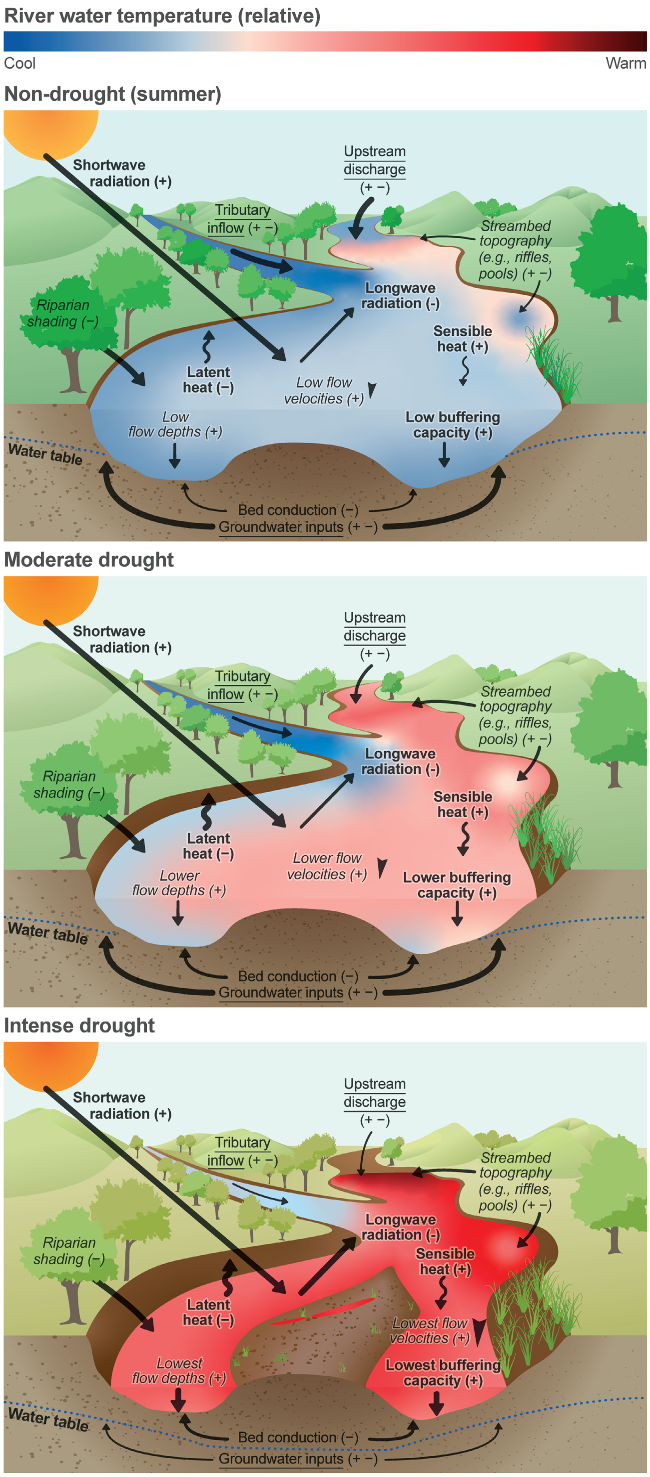

FIGURE 4 Changes in the relative influence of dominant heat fluxes governing river water temperature (T_w) during routine low-flow conditions and different drought severities. Thin, moderate and thick lines denote small, intermediate and large relative effects, respectively. Emboldened, italicized and underlined text denotes mechanisms comprising the 'energy flux dynamics', 'reach-scale habitat conditions' and 'water source contributions' process sets, respectively.

and lower atmospheric humidity. Bed conduction will also typically cool rivers during drought conditions as benthic habitats will typically be characterized by lower temperatures than the overlaying water column (particularly in many groundwater-dominated systems). As drought intensifies, the influences of upstream advective fluxes on T_w will be dampened, which could have varying effects depending on the thermal properties of contributing tributaries. Declining river discharges are likely to increase T_w via a reduced thermal buffering capacity. Groundwater inputs may become equally or more important during low-moderate drought intensities (as surface waters recede at faster rates), while extreme droughts lowering water tables can disconnect such subsurface inputs and thus lessen its influences on T_w. The shading effects of dense and tall riparian vegetation is likely to be highly influential across various drought intensities. Declining flow depths with drought severity has the potential to increase T_w as shortwave radiation can penetrate further into the water column, while reduced stream velocities will exacerbate this warming effect by increasing residence times.

4 | HUMAN INFLUENCES AFFECTING RIVER WATER TEMPERATURE DURING DROUGHTS

The following section focusses on four key human influences affecting T_w during droughts: (i) riparian vegetation modifications; (ii) flow regulation; (iii) water abstraction; and (iv) channelization (physical modifications to river channels). Pressures and management interventions associated with these human activities are reviewed and discussed.

4.1 | Riparian vegetation clearance and planting

A limited number of studies have empirically assessed the effects of riparian clearance and planting on T_w (e.g., Neal et al., 1992; Stott & Marks, 2000—see Table 2). However, most research characterizing the effects of anthropogenically-induced riparian vegetation modifications on summer T_w values have employed space-time substitutions comparing covered (forested) versus open reaches (Broadmeadow et al., 2011; Webb & Crisp, 2006), some of which also quantify differences in solar radiation reaching the water surface (Bachiller-Jareno et al., 2019; Dugdale et al., 2018; Hannah et al., 2008). Various studies have employed modelling techniques to predict where riparian planting management initiatives could most effectively reduce T_w. For instance, in northeast Scotland, Garner et al. (2017) suggested that planting on the southerly bank of river reaches with an E-W orientation that possess lower flow velocities (i.e., longer residence times) would yield the greatest reduction in peak T_w values during a compound drought-heatwave. In central England, Johnson and Wilby (2015) reported that ~0.5 km of complete shading would reduce July T_w values by 1°C in headwater sites, but ~1.1 km was required in reaches 25 km downstream (see also Davies-Colley et al., 2009; Jackson et al., 2021; Kaandorp et al., 2019). Evidence from studies empirically testing and modelling the effects of riparian vegetation on T_w, including during droughts (and compound drought-heatwaves), could be more widely considered in catchment-wide management objectives aiming to deliver other environmental and ecological objectives (e.g., spatially prioritizing riparian planting versus maintaining some open channels to conserve iconic macrophyte communities).

4.2 | Flow regulation

The effects of flow regulation on T_w depend on a multitude of confounding factors, including antecedent hydroclimatic conditions, the location of the reservoir in the catchment, inflowing thermal characteristics, water residence times, bathymetry, the potential for thermal stratification and the extent to which impounded waters are mixed, draw off depth and the type of reservoir operation (e.g., water supply, hydropower; Olden & Naiman, 2010; Webb & Walling, 1993, 1997). Scientific investigations on the effects of reservoirs on downstream T_w variations have been undertaken non-systematically, and inferring generalizable thermal responses is therefore challenging. There remains a fundamental lack of understanding on how different reservoir properties collectively govern T_w, including during drought conditions where flow releases could exacerbate of mitigate thermal peaks (Cowx et al., 1987). Various studies from Cfb climates have reported a thermal 'compressing' effect of water supply reservoirs on annual T_w ranges, whereby summer discharges specifically are cooled by continuous compensation flow releases that restrict the occurrence of extreme low-flows and thus thermal peaks (Krajenbrink et al., 2022; Webb & Walling, 1993, 1997), although such trends are inconsistent. For instance, Cowx et al. (1987) reported that one regulated system possessed T_w values ∼2°C cooler than a nearby free flowing river during the summer 1976 drought, but another impounded river was ∼0.5°C warmer during the same event; the author also reported that the thermal effects of each reservoir were broadly comparable between drought and non-drought years. Webb and Walling (1997) reported that summer T_w values in a regulated system were consistently warmer (up to ∼2°C) than those in nearby free flowing rivers during the 1989, 1992 and 1995 droughts (albeit less convincingly for the latter) due to the high residence time of impounded waters upstream.

Reservoir destratification measures are the most widely implemented method of preventing thermal modifications in regulated systems worldwide (see Olden & Naiman, 2010). Such measures are often introduced to reduce the downstream release of poor water quality conditions (and often colder waters) from the hypolimnion, which can reduce downstream T_w modifications (Cowx et al., 1987). In southwest England, Webb and Walling (1997) found that thermal stratification occurred despite the implementation of aeration systems. Subsequently, declining reservoir water levels meant that discharges released downstream were drawn from deeper, cooler offtakes. Finally, inter-basin transfer schemes between impounded systems can alter the thermal dynamics of rivers depending on the size and T_w regimes of the donor and receiving waterbodies. For instance, Krajenbrink et al. (2022) found that a water transfer scheme reversed the summer cooling effect of a reservoir as the donor basin yielded warmer water temperatures, thus elevating daily mean T_w values by 5°C during a non-drought summer; although evidence on the implications of such inter-basin water transfer schemes on T_w is limited globally.

4.3 | Water abstraction

Water abstraction for public water supply can occur via online (surface water) or groundwater withdrawals, which have the potential to elevate T_w during drought by lowering discharges, hence reducing thermal buffering capacity of watercourses and reducing flow depths and velocities. However, such abstraction effects will be contingent upon factors like water volumes withdrawn (i..e, proportion of river discharge lost) and water source contributions. For instance, in northeast Scotland Fennell et al. (2020) found that T_w variations during the 2018 drought were not evidently affected by abstractions as discharges were heavily buffered by cool groundwater inputs. Similarly, on the north island in New Zealand, Dewson et al. (2007) experimentally reduced in-channel discharges during summer months to reflect plausible regional abstraction practices and reported T_w decreases due to greater proportional groundwater inputs. However, further research is needed to extrapolate associations between river discharge-T_w to observed or modelled abstraction effects.

Abstraction volume reductions and licensing are internationally implemented to limit their environmental impacts during drought, including 'Hands-off Flow' restrictions that enforce licence holders to reduce or cease abstraction practices when river discharges fall below a specific threshold (Acreman et al., 2008). However, the lagged effects of groundwater abstraction on the flow regimes of aquifer-fed, hydrologically buffered river systems means that such reactive measures are typically not feasible (White et al., 2021). Consequently, low-flow alleviation schemes in regions underlain by aquifers can involve pumping groundwater directly into channels when discharges fall below a certain threshold, which can yield cooling effects during extreme low-flows (e.g., Wilby, 1993). However, thermal considerations are widely neglected within such environmental flow strategies (Olden & Naiman, 2010) and there remains a limited scientific understanding on this topic.

4.4 | Channelization

Channel modifications undertaken to meet various human demands (e.g., for navigation, erosion and flood protection) have varying implications for T_w dynamics. The implications of modified hydraulic geometries from channel overdeepening and overwidening has been discussed previously. Channelization can also modify T_w dynamics by simplifying hydraulic variations and habitat heterogeneity, thus limiting hyporheic exchanges between groundwater and surface water (Magliozzi et al., 2019); particularly in urban rivers possessing concrete-lined beds. This may facilitate higher T_w values during droughts in channels when cold subsurface water inputs that normally occur in habitats such as riffle tails (Hannah et al., 2009) or groundwater-fed pools (Kaandorp et al., 2019) are absent.

River restoration practices have been widely advocated as a means of reinstating the ecological and physical integrity of water-courses and geomorphological processes. However, restoring water quality variables like T_w regimes is rarely a primary motive for such morphological interventions, despite its clear implications. For instance, weir removals have the potential to reduce summer thermal peaks during droughts as 'ponded' reaches can warm rapidly (Johnson et al., 2014). Restoring channel planforms (e.g., re-introducing sinuosity) will affect T_w as this alters the orientation and length of the water-course (and hence the volume of water exposed to atmospheric energy exchanges; Garner et al., 2017), as well as through modifying morphological variability and hyporheic exchanges (Hannah et al., 2009). More holistic, catchment-wide approaches to river restoration are required that consider how high T_w extremes can be offset while delivering other environmental and ecological benefits. For instance, natural flood management measures that increase flow residence times by holding back water volumes could be introduced alongside riparian planting initiatives, whereby river reaches exposed to atmospheric influences for longer periods receive greater protection from shortwave radiation inputs.

5 | MODELLING RIVER WATER TEMPERATURE UNDER DROUGHT CONDITIONS

In this review, we have highlighted how various studies across Cfb climate zones have provided a critical understanding of the key processes shaping T_w during hot and dry conditions. However, various knowledge gaps still exist that limit our scientific capacity to predict T_w spatial and temporal dynamics to historic and future drought events. Novel scientific approaches examining the interactive influences of mechanisms spanning different process sets are therefore urgently required to better inform T_w models. Such advances that can better estimate where and when high river thermal extremes occurring during droughts would help guide evidence-led management initiatives and adaptation strategies (Figure 5).

Existing T_w models are predominantly categorized into two classifications: 'process-based' or 'statistical'. Process-based models simulate the real-world transfers of energy and mass that control T_w, while statistical models aim to quantify linkages between T_w and various relevant covariates, particularly air temperature (as a proxy for net energy exchange) and discharge (for further information, see Benyahya et al., 2007; Dugdale et al., 2017). The variety of available statistical models has evolved drastically in recent years, which has enhanced their spatial coverage and predictive capacity. This includes different linear or logistic regression-based approaches, as well as machine learning techniques like random forest models and deep learning neural networks (Feigl et al., 2021; Piotrowski et al., 2021). In addition, various 'hybrid' T_w models have also emerged that integrate principles from statistical and process-based models by defining a physically based model structure, with parameters estimated through stochastic calibration (the 'air2stream' being a notable example—Piotrowski et al., 2021). However, there remains a limited number of T_w modelling studies that have specifically tested predictions during drought conditions. In this section, we highlight and discuss five critical research questions surrounding modelling approaches that need to be addressed to better predict drought-induced T_w dynamics. We do so by reporting examples of T_w models implemented globally (although emphasis is placed on examples from Cfb and other temperate climates) that require further testing and implementation across different drought severities (intensities and durations).

5.1 | Which present day and future hydroclimatic conditions characterizing drought should be modelled?

Although some process-based (Garner et al., 2014, 2017) and statistical (Beaufort et al., 2022; van Vliet et al., 2011, 2013) T_w modelling studies have incorporated high air temperatures and extreme low-flow conditions, such approaches most typically focus on seasonally typical summer conditions (Jackson et al., 2018, 2021; Kaandorp et al., 2019). This represents a major limitation as drought-induced T_w predictions would be beyond the calibration range of the training dataset collected during non-drought conditions. For process-based models, many of the underpinning energy fluxes have been largely untested during extreme droughts, including the performance of empirical or semi-empirical approaches widely employed to estimate latent heat exchanges (Garner et al., 2014, 2017). Solar radiation receipts incorporated within large-scale process-based models will experience greater uncertainty for this as the underpinning energy flux estimates are derived at coarser spatial scales (Jackson et al., 2021; Johnson & Wilby, 2015). Modelling future T_w predictions requires input variables from climate change projections. Air temperature, precipitation and changing river flows are consistently exported from climate model experiments (e.g., Lowe et al., 2019), which can be used to underpin statistical-based models (van Vliet et al., 2011, 2013). However, caution should be exercised when assuming stationarity in drought conditions, as is widely applied within T_w models (particularly statistical models), given that the duration and severity of such events are likely to increase in the future (AghaKouchak et al., 2020). Conversely, data on energy budget controls like solar radiation are less common, which depicts a key limitation for process-based models estimating future drought-induced T_w dynamics.

5.2 | How can hydraulic conditions reflecting drought be incorporated into river water temperature models?

Various process-based models include a hydraulic routing component (e.g., HEC-RAS—Saleh et al., 2013), which often use a formulation of

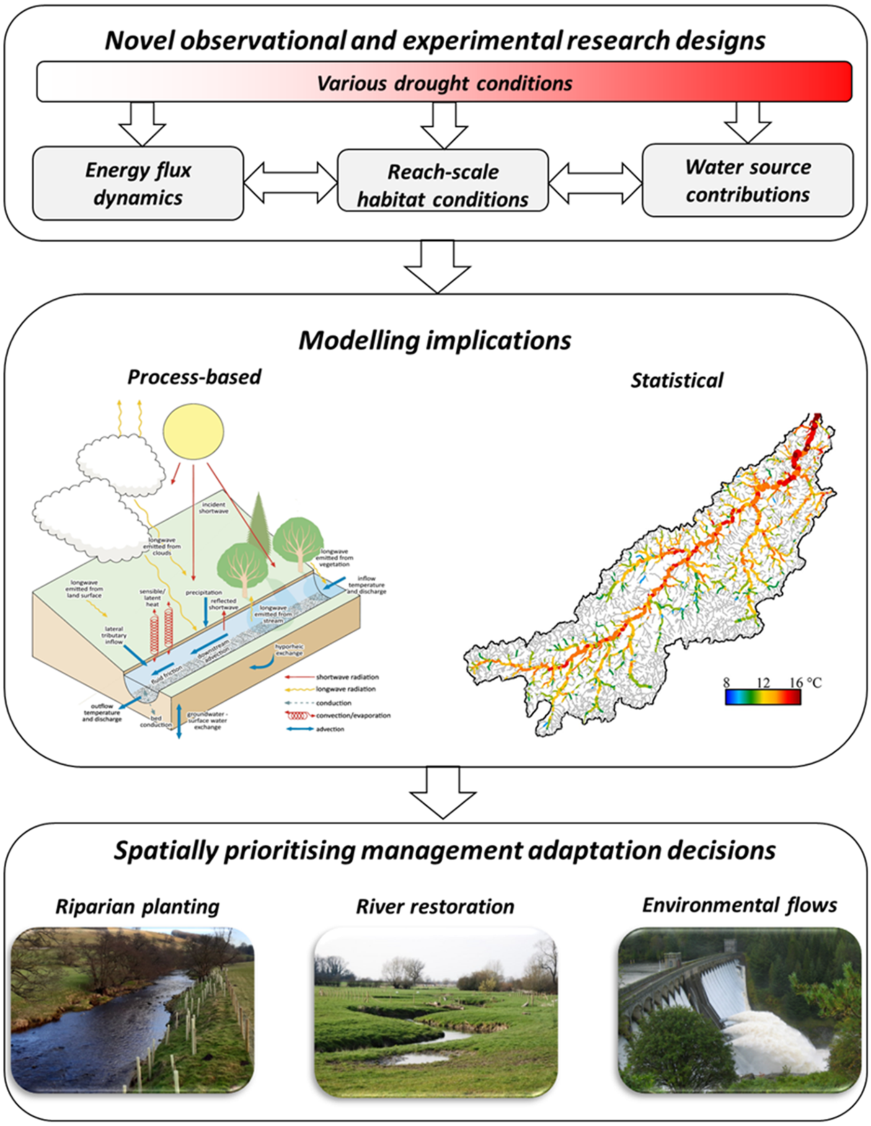

FIGURE 5 A schematic flow chart highlighting that different types of new scientific evidence are required to answer critical research questions surrounding river water temperature (T_w) dynamics during droughts and how this could inform management adaptation decisions. Photo credit: 'Process-based model'—reprinted with permission from Dugdale et al. (2017; Fig. 1); 'Statistical model'—reprinted with permission from Jackson et al. (2017; Fig. 5a); 'Riparian planting'—reprinted with permission from Ribbles Rivers Trust; the 'River restoration' ('River restoration of the River Cole—geograph.org.uk—1210054.jpg') and 'Environmental flows' ('Laggan Dam in full flow—geograph.org.uk—3006049.jpg') images have been obtained from the website 'Wikimedia', where they have been made available under a CC BY-SA 2.0 licence. These images are attributed to Simon Mortimer and Jennifer Jones, respectively, who uploaded the images.

the St-Venant equations to simulate flow velocity and depth. However, under extreme low-flow scenarios where the bed roughness height approaches the water depth, stable solutions to these equations can be difficult to achieve (Saleh et al., 2013). Consequently, such models often have difficulty accurately simulating water velocity and depth, potentially leading to inaccurate T_w estimates. The use of such hydraulic models has been most widely utilized within North America and often tailored towards high-flow events (Dugdale et al., 2017), and should be more widely adapted and parameterised to extreme low-flow conditions and applied across different climates (including Cfb zones) and channel morphologies. For statistical models spanning large spatial scales, incorporating hydraulic geometry is far more challenging (Benyahya et al., 2007). Estimates of channel slope and width can be derived from GIS information (Jackson et al., 2021), but hydrological information is also required to estimate hydraulic responses to changing flow conditions. Such associations are typically derived from velocity-discharge relationships obtained at flow gauging stations, which can be obscured by unnatural river cross-sections and are typically limited in their spatial extent (see below).

5.3 | How can hydrological and river water temperature models be more effectively integrated?

Hydrological data is most widely available via flow gauges that can provide long-term river discharge timeseries at high temporal resolutions, but are spatially discrete in nature and often biased towards larger rivers. The lack of spatial integration between discharge and T_w measurements in smaller channels restricts the quality and quantity of training data available for modelling. Hydrological models can provide an alternative means of deriving spatially continuous river discharge data, but can face various challenges (particularly in smaller headwater channels) predicting hydrological processes like discharge variations, groundwater disconnections and flow cessation events during droughts (White et al., 2018). This is a particular knowledge gap as recognizing where different water source disconnections occur, either through upstream advective inputs (i.e., drying events or instream ponding) or groundwater inputs is critical for recognizing T_w shifts during drought conditions. However, some hydrological models can help identify the effects of different water source contributions on T_w during drought conditions. For instance, during a non-drought year in northeast Scotland, Fabris et al. (2018) combined process-based T_w and hydrological ('MIKE 11') models to predict the effects of both surface water and groundwater contributions on river thermal properties alongside hydraulic influences and riparian vegetation coverage. Statistical models estimating spatially continuous T_w often quantify the effects of upstream advective inputs via stream order as a surrogate for river discharges (e.g., Beaufort et al., 2016; Jackson et al., 2017, 2018), which although practical at large spatial scales overlooks the nuances of flow regime variations, including during drought conditions.

5.4 | How can human activity influences on river temperature be quantified and modelled?

The management of riparian vegetation has been explored within different process-based models capturing chanel shading effects (Bachiller-Jareno et al., 2019; Jackson et al., 2021). Process-based T_w models can more readily incorporate the influences of other human activities by parameterising their effects operating within a single or smaller number of systems, including the hydrological and hydraulic influences of flow regulation below dams (Wawrzyniak et al., 2017). This becomes more challenging for T_w models spanning large spatial scales as the effects of human modifications like the flow regulation effect of dams and channel modifications can vary drastically within and between river catchments. However, spatially continuous estimates of morphological pressures or sub-reach flow properties (Magliozzi et al., 2019; Naura et al., 2016) could help characterize hydraulic geometries that mediate channel velocities and width: depth ratios. Moreover, hydrological models can provide a measure of surface and subsurface water management influences on river discharges across river networks (White et al., 2018, 2021), which could also help refine and identify various future drought scenarios exacerbated by human activities.

5.5 | How can we more effectively model the effects of different management interventions to prioritize management?

Despite an increasing number of T_w modelling studies being undertaken, there remains a lack of such research tailored to guiding the spatial prioritization of river management interventions. Some statistical T_w models have been used to identify locations vulnerable to high thermal extremes during low-flow conditions across large geographical coverages (up to national scales—Beaufort et al., 2022; Jackson et al., 2018), although such outputs have rarely been tailored to directly informing management interventions. While process-based models have been historically regarded as being highly parameterised and difficult to apply large spatial scales (Dugdale et al., 2017), computational advances have now allowed solar radiation receipts to be quantified across river grid cells globally, and a limited number of studies have used this to help guide management interventions. For instance, Jackson et al. (2021) provided a simplified process-based T_w modelling approach that allowed estimates of riparian shading, solar radiation receipt, river discharge, hydraulic conditions (residence times) and an array of landscape and channel characteristics to be projected across large spatial scales. From this, the authors derived a planting prioritization metric to indicate where afforestation would likely yield the greatest reductions in incoming radiation and summer T_w. While other studies have used process-based T_w models to provide guidance on where planting could reduce high thermal extremes (e.g., Davies-Colley et al., 2009; Johnson & Wilby, 2015), such examples have been most consistently related to typical summer low-flows and not tailored to drought conditions. However, neither T_w modelling approaches have been widely used to highlight and spatially prioritize alternative management approaches like river restoration strategies or the application of environmental flows; although incorporating measures of hydraulic geometries and hydrological alterations (outlined above) could help prioritize and tailor such interventions to reach-specific conditions.

6 | CONCLUSION

Drought events often co-occur with warm climatic conditions, and such conditions (including compound drought-heatwaves) are expected to become more intense and frequent with climate change. As such, drought events have significant implications for river water temperature (T_w) extremes due to the combined effects of intense solar radiative forcings and lower river discharges; the latter reducing flow depths, flow velocities (i.e., enhancing residence times) and the overall thermal buffering capacity of watercourse. However, T_w increases during droughts are contingent upon complex interactions between mechanisms operating across three key 'process sets' that we identified in this review: (i) 'energy flux dynamics' (non-advective controls); (ii) 'reach-scale habitat conditions'; and (iii) 'water source contributions' (surface water and groundwater advective inputs). We have synthesized evidence of T_w responses to droughts and the mechanisms governing this across temperate, maritime climates, using the UK as a detailed case study. We reviewed how such T_w controls are influenced by natural and anthropogenic controls, and where certain management interventions (e.g., riparian planting, environmental flows, river restorations) can modify these processes to try and offset high thermal extremes during droughts. From this, we identified critical knowledge gaps and research questions on T_w modelling approaches that should be pursued to better predict the occurrence of high thermal extremes during drought events. These scientific advances will be fundamental to underpinning evidence-led management interventions aiming to protect freshwater ecosystems from rising T_w associated with anticipated increasingly frequent and severe drought episodes.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are freely available in the public domain from the following sources: 'Environment Agency's' Water Quality Archive (https://environment.data.gov.uk/water-quality); Environment Agency's 'Hydrology Data Explorer' (https://environment.data.gov.uk/hydrology); and UK Centre for Ecology and Hydrology's 'National River Flow Archive' (https://nrfa.ceh.ac.uk/).

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SUPPORTING INFORMATION

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

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