A climate change report card for water

Working Technical Paper

3. Changes in UK river water temperature over the 20th century and possible changes over the 21st century

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EXECUTIVE SUMMARY

- This Technical Report provides the background to support the LWEC Report Card on "Changes in UK river water temperature over the 20th century and possible changes over the 21st century" by synthesising the existing research with a focus on peer-reviewed academic literature. The emphasis of this report is on the UK, although pertinent international research is reviewed to contextualise UK-based information. Throughout, the term 'river temperature' refers to water column temperature in the river channel. Riverbed temperature is not considered in detail.
- River temperature is an important and highly sensitive variable affecting physical, chemical and biological processes in flowing waters. There are clear ecological and socio-economic benefits to be accrued from: (1) understanding the sensitivity of river temperature to climate change and other drivers of change using observations for the 20th century, and (2) assessing possible future river temperature changes in the 21st century to inform management and adaptation strategies.
- River water is controlled by dynamic energy (heat) and hydrological fluxes at the air-water and water-riverbed interfaces. Land and water management impact on these drivers and, thus, modify river thermal characteristics.
- Spatial and temporal variability in climatological, hydrological (hydraulic), land use, sedimentary and geomorphological controls on heat flux and hydrological processes create heterogeneity in river temperature at a range of scales.
- On top of other drivers of change, it may be anticipated that climate change will have direct and indirect impacts on river temperature. Under climate change, direct effects may occur due to shifts in the energy exchange and hydrological processes. Indirectly river temperature may be affected by climate change induced alteration of riparian land use and human response to potential reduced water security.
- Most previous UK river temperature studies using observational data have been: (1) restricted to the basin scale; (2) short-term or seasonally-constrained to summer with very few long-term year-round and multi-year studies, and (3) focused primarily on unravelling the role of site-specific factors and conditions. Consequently, there is a serious lack of research on spatial and temporal variability and the controls on river temperature at the inter-basin to region-scale and beyond over long time periods during the 20th century.
- It is evident from the international (including UK) literature that variability in river temperature over the 20th century is a complex, dynamic response to climate patterns and hydrological change moderated by basin properties and anthropogenic impacts.
- Probably the longest-term and most spatially widespread assessment of river temperature for the UK uses data from the Environment Agency Surface Water Temperature Archive (des Clers *et al.*, 2010; Orr *et al.*, 2010). Using, using 3,157 sites from the Archive a mean annual water temperatures increase across England and Wales of 0.29°C decade^{-1} (1990- 2006) is reported, which is linked to air temperature trends but no supporting analysis is conducted of hydrological or other river basin processes.
- The most comprehensive work on future climate change impacts on river temperature has been conducted in North America. For the UK, there are very, very few predictive modelling studies of river temperature under climate change. Hence, there is scant evidence to evaluate what may happen to UK river temperature in the 21st century.
- There is much uncertainty over river temperature change because responses may vary widely across large geographical areas and future water temperature predictions depend on

the climate scenario applied. Furthermore, climate change will alter hydrology and basin/ site characteristics, and so moderate river temperature. Consequently, the spatial patterns in future river temperature may differ from those projected for driving climate variables. As well as spatial differences, river temperature responses may vary seasonally possibly reflecting future change in influential climatic variables, and/ or seasonal contrasts in the sensitivity of rivers to the effects of climate change.

- Confidence in the science on WHAT HAS HAPPENED?: (1) Medium level of agreement on the influence of climatological, hydrological, land-use and anthropogenic controls on UK river water temperature. (2) Medium level of agreement and as likely as not that UK river temperature has increased over the latter of the 20th century. (3) Low agreement on the attribution of UK river temperature changes over the latter of the 20th century to drivers of change, in particular climatic warming.
- Confidence in the science on WHAT MAY HAPPEN IN THE FUTURE?: Medium level of agreement and as likely as not that UK river temperature will increase in the 21st century; however, there are a number of interlinked sources of uncertainty (above) that mean estimating rates of river temperature change for sites across the UK is beyond current knowledge.
- A number of priority knowledge gaps are emergent that need to be addresses to improve understanding of past, contemporary and future river temperature change; these relate to: monitoring network, metadata, understanding river thermal heterogeneity across multiple scales, robust analysis to detect river temperature change, systematic attribution to drivers of change, quantification of river temperature sensitivity to drivers of change, and improved future projections accounting forsources of uncertainty.
- Understanding, with a high level of confidence, how river temperature dynamics will change during the 21st century is vital for a range of socio-economic activities.

REPORT SCOPE AND STRUCTURE

This Technical Report provides the background to support the LWEC Report Card on "Changes in UK river water temperature over the 20th century and possible changes over the 21st century" by synthesising the existing research with a focus on peer-reviewed academic literature. The emphasis of this report is on the UK, although pertinent international research is reviewed to contextualise UK-based information. Throughout, the term 'river temperature' refers to water column temperature in the river channel. Riverbed temperature is not considered in detail.

The report is structured as follows: (1) background RESEARCH CONTEXT is provided to highlight the importance of river temperature research in a changing climate and situate this report with respect to previous reviews, (2) state-of-the-art UNDERSTANDING of PROCESSES, CONTROLS, DYNAMICS AND DRIVERS OF CHANGE is reviewed to provide a strong science basis for evaluating findings in this report, (3) changes in UK river temperature over the 20th century are evaluated with reference to the wider international literature to assess WHAT HAS HAPPENED ?, (4) WHAT MAY HAPPEN IN THE FUTURE? is speculated based on the very limited number of predictive modelling studies of possible UK river temperature over the 21st century with findings contextualised by international research, (5) CONFIDENCE IN THE SCIENCE reviewed in the previous two sections (3 & 4) is considered and, where appropriate, qualified using the confidence and likelihood terms for the IPCC AR5; (6) emergent priority KNOWLEDGE GAPS are listed to provide guidance on how to improve understanding of past, contemporary and future projections of river temperature change in the UK, and (7) finally the SOCIO-ECONOMIC IMPACTS of UK river temperature change are discussed.

RESEARCH CONTEXT

River temperature is an important and highly sensitive variable affecting physical, chemical and biological processes in flowing waters (Caissie, 2006). There are clear ecological and socio-economic benefits (see SOCIO-ECONOMIC IMPACTS) to be accrued from: (1) understanding the sensitivity of river temperature to climate change and other drivers of change using observations for the 20th century, and (2) assessing possible future river temperature changes in 21st century to inform management and adaptation strategies (Wilby *et al.*, 2010). As a consequence of the increasingly recognised importance of river temperature, there has been a recent upsurge in research on this master water quality variable (Hannah *et al.*, 2008a.).

There are four comprehensive reviews of the river temperature literature. In chronological order, Smith (1972) considers the physical process driving river temperature variability in near-natural systems and also evaluated human impacts that include thermal pollution. Ward (1985) focuses on the Southern Hemisphere to consider controls on the thermal regime and anthropogenic factors. Cassie (2006) overviews water temperature modelling, natural and human influences on thermal conditions and implications for aquatic ecology. Most recently, Webb *et al.* (2008) capture renewed interest by evaluating significant advances in river and stream temperature research since 1990. Notably, Webb *et al.* (2008) identify improving understanding of: (1) thermal heterogeneity at different spatial and temporal scales and (2) past and future trends as major issues for contemporary river temperature research. Such understanding is required urgently by environment regulators as a first step in assessing how climate changes will alter river systems and interact with other pressures affecting ecological status and societal use of flowing waters.

UNDERSTANDING PROCESSES, CONTROLS, DYNAMICS AND DRIVERS OF CHANGE

Processes

River water is controlled by dynamic energy (heat) and hydrological fluxes at the air-water and water-riverbed interfaces (Figure 1; Hannah *et al.*, 2008b.). Land and water management impact on these drivers and, thus, modify river thermal characteristics (Webb *et al.*, 2008). For a specific point on a river, water column temperature is determined initially by the mix of water source contributions (surface/ shallow sub-surface flows, groundwater, snow melt etc.) and subsequently the energy gained or lost across the water surface and riverbed interfaces as the river flows downstream. Thus, spatial and temporal variability in heat flux and hydrological processes create heterogeneity in river temperature at a range of scales.

Heat transfer within river systems is complex, occurring by a combination of: radiation, conduction, convection and advection (Webb & Zhang, 1997). These energy exchanges add and remove heat to and from the river. Inputs may occur by: incident short-wave (solar) and long-wave (downward atmospheric) radiation, condensation, friction at the channel bed and banks, and chemical and biological processes. Losses may include: reflection of solar radiation, emission of long-wave (back) radiation and evaporation. Sensible heat and water column-bed energy transfers may cause gains or losses. In addition to these exchanges, energy may be advected by: in/out-flowing channel discharge, evaporated water, groundwater up/down-welling, tributary inflows and precipitation. All these heat fluxes may be related together using a heat budget (energy balance) to give the total energy available to heat or cool river water (Q_n):

$$Q_n = Q^* + Q_h + Q_e + Q_b + Q_f + Q_a \qquad \text{(Equation 1)}$$

where Q^* = net radiation, Q_h = sensible heat, Q_e = latent heat, Q_b = bed conduction, Q_f = friction at the bed and banks, and Q_a = heat advection by precipitation and groundwater.

For a river reach without strong longitudinal in-channel thermal gradients and no tributary or groundwater inflows, the change in water temperature over time (ΔT_w) may be simplified to:

$$\Delta T_w = Q_n / (\rho\ C_p\ d) \qquad \text{(Equation 2)}$$

Where: ρ = density of water, C_p = specific heat capacity of water, and d = mean river depth.

Despite the utility of the energy balance as an analytical tool and for river temperature prediction, few empirical studies have attempted to quantify energy balance components over rivers; and most existing heat balance studies are short-term, that is days (Hannah *et al.*, 2004). For the UK, river energy balance studies have been confined geographically to the chalk streams (e.g. Webb and Zhang, 1997, 1999, 2004) and regulated rivers (e.g. Evans *et al.*, 1998) of central and southern England, and the Scottish Cairngorm mountains (Hannah *et al.*, 2004, 2008b.).

Controls

Several studies have attempted to disentangle the multivariate influence of the wide range of factors that control the above energy fluxes and hydrological processes and, ultimately, river temperature. Solar (short-wave) radiation inputs are reduced by shading effects, most notably topography (e.g. incised channels; Webb & Zhang, 1997) and overhanging vegetation (e.g. riparian forest cover as reviewed by Moore *et al.*, 2005). Long-wave radiation is received from the atmosphere plus surrounding terrain and vegetation in proportion to their view factors (Rutherford *et al.*, 1997) and emitted from the river at its surface temperature.

Sensible heat transfer is dependent on the air-water temperature gradient and turbulent mixing (forced by wind speed) with heat gained from a warmer overlying air and lost from a warmer water surface. Latent heat exchange relates to water phase change, with energy released to warm the river by condensation and heat consumed by evaporation from the water surface (Hannah *et al.*, 2004). Evaporation and condensation are influenced by the humidity gradient between the water surface and overlying air and turbulent mixing. Thus, river exposure (openness) and sheltering are important in determining the magnitude of sensible and latent heat fluxes (Johnson, 2004).

Atmospheric conditions and river depth are well documented controls on river thermal patterns (e.g. Webb & Zhang, 1997); but many studies have ignored largely or assumed negligible heat fluxes at the channel-bed interface (cf. Evans *et al.*, 1998; Hannah *et al.*, 2004, 2009). The energy balance at the riverbed interface is the sum of net radiative, conductive, convective and advective fluxes (Hannah *et al.*, 2009). The direction (source or sink) and relative contribution of heat exchanges at the water column-bed compared with the air-water interface varies temporally (Webb & Zhang, 2004; Hannah *et al.*, 2004, 2008), and spatially (between and within river systems; cf. Evans *et al.*, 1998; Hannah *et* *al.*, 2004; Krause *et al.*, 2011; O'Driscoll & DeWalle, 2006; Storey *et al.*, 2003). Channel-bed thermal gradient and thermal conductivity (for conduction), water depth and bed albedo (for radiation) and phreatic and hyporheic flows (for convection and advection) determine riverbed heat transfers, which are controlled locally by factors including: bed morphology, bed sediment size and lithology, substratum permeability and porosity, algal and macrophyte growth, and flow hydraulics (as reviewed by Hannah *et al.*, 2009). Typically, the bed heat flux cools the river in summer when advected groundwater is cooler than the water column, and warms the river in winter when the situation is reversed (Malcolm *et al.*, 2004a.). Thus, groundwater may moderate strongly river temperature variability (Malcolm *et al.*, 2005).

River Temperature Dynamics

The thermal behaviour of rivers may be highly spatially and temporally variable due to the climatological, hydrological (hydraulic), land use, sedimentary and geomorphological controls discussed above.

Temporal patterns. River temperature varies seasonally and diurnally in response to dominant solar forcing of climate conditions, with day-to-day thermal variability the result of prevailing weather conditions. Diurnal cycles are at lowest amplitude in winter and greatest in summer (e.g. Malcolm *et al.*, 2004b.). Webb & Walling (1992) identified more pronounced diurnal cycles in spring than autumn for three rivers in southwest England. Long-term studies of year-to-year variation in river temperature are lacking seriously in the literature. Those studies that do exist tend to focus on human impacted systems, notably forestry (reviewed by Moore *et al.*, 2005) or dam impoundment (e.g. Webb & Walling, 1988, 1993), and thus are confounded in terms of detecting and attributing climate change effects. The few long-term studies are reviewed in the WHAT HAS HAPPENED? section (below).

Spatial patterns. Thermal dynamics vary within and between river basins. Rivers fed by major groundwater aquifers tend to be cooler with less diurnal and seasonal variability than rivers in less permeable basins (Caissie, 2006). Locations with increased thermal capacity and longer water travel times (Hrachowitz *et al.*, 2010; Webb *et al.*, 2008; Webb & Nobilis, 2007;) also often display less thermal variability. Local deviations for the typical downstream warming trend (due to elevation change and increased atmospheric exposure time) may be caused by changes in riparian land use, groundwater inflows, hyporheic exchange, and presence of lakes and wetlands (Chu *et al.*, 2010; Mellina *et al.*, 2002; Poole & Berman, 2001). At the micro-scale, Clarke *et al.* (1999) explore sub-reach water column variability and identify thermal contrasts with temperature up to 7°C higher for vegetated in-channel marginal zones compared with the main flow. Strong evidence of stratification for small river pools is absent in the literature, although large pools may stratify (Nielsen *et al.*, 1994).

Drivers of Change

There are a number of drivers of change that influence controls on the energy balance and water fluxes and so river temperature. The impacts of forestry practice are the best documented and the somewhat contradictory findings are synthesised and evaluated by Moore *et al.* (2005), with a UK focus provided by Hannah *et al.* (2008b.). Land use change from riparian forest to grassland for agriculture may elevate river temperature in summer (e.g. Isaak & Hubert, 2001; Li *et al.*, 1994). Urbanisation is associated with increased river temperature compared with rural environments due to runoff of water across warmed paved surfaces (e.g. Herb *et al.*, 2008; Kaushall *et al.*, 2010) and channel widening/ vegetation removal (i.e. exposure) to increase flow conveyance (Klein, 1979). Direct flow augmentation and abstraction change river thermal capacity, hence river temperature. Heated effluent from power plants and other point sources may have a profound warming impact (e.g. Maderich *et al.*, 2008). The thermal effects of reservoirs are well documented for the UK, USA and elsewhere by Webb & Walling (1997).

On top of these drivers of change, it may be anticipated that climate change will have direct and indirect impacts on river temperature. Under climate change, direct effects may occur due to shifts in the energy exchange and hydrological processes that determine river temperature. Indirectly river temperature may be affected by climate change induced alteration of riparian land use and human response to reduced water security.

WHAT HAS HAPPENED?

This section reviews changes in UK water temperature over the 20th century and draws on the international literature to set this information in a wider context.

Research on river temperatures in the UK has investigated (Table 1):

- point-scale heat fluxes that control fundamentally water temperature (see also UNDERSTANDING PROCESSES);
- reach-scale variability in the water column (e.g. Carling *et al.*, 1994; Clark *et al.*, 1999) and riverbed (e.g. Hannah *et al.*, 2009; Krause *et al.*, 2011);
- effects of forestry (e.g. Weatherley & Ormerod, 1990; Crisp, 1997; Stott & Marks, 2000; Hannah et al., 2008b.; Broadmeadow et al., 2011);
- spatial and temporal dynamics across river networks (e.g. Crisp *et al.*, 1982; Hrachowitz *et al.*, 2010; Imholt *et al.*, 2011; Webb & Walling, 1986; Webb & Walling, 1992; Webb *et al.*, 2003)

This research has yielded significant new knowledge about UK river temperature patterns, controlling factors and driving mechanisms. However, most previous UK studies have been: (1) restricted to the basin scale; (2) short-term or seasonally-constrained to summer with very few long-term year-round and multi-year studies, and (3) focused primarily on unravelling the role of site-specific factors and conditions. Consequently, there is a serious lack of research on spatial and temporal variability and the controls on river temperature at the inter-basin to region-scale and beyond over long time periods during the 20th century.

Internationally, long-term and wide spatial coverage river temperature studies are extremely rare because of a lack of reliable unbroken records. Most river temperature time-series span only a few years (Caissie, 2006). Webb *et al.* (2008) reviewed the few long term studies and comment that, despite most studies indicating warming, "*considerable variation in the magnitude of river temperature rise is apparent between and within river systems*" (p. 910). For the USA, Webb (1996) reported trends for 90 out of 364 rivers studied from 1974-1981. However, when temperature data are flow-adjusted, only 29 rivers exhibit significant trends with 22 rivers warming as flows declined and 7 rivers cooling with increased flows. Interestingly, clear regional patterns related to hydroclimatological regimes did not emerge due to local effects of forestry, land use, flow regulation and heated effluent discharge (Webb, 1996). More recently, Kaushal *et al.* (2010) analysed data for 40 major USA rivers and showed significant, long-term warming trends for 20 rivers that were significantly correlated with air temperature. Rates of warming were most rapid in urban areas, although no further detailed interpretation is provided of controls.

Webb & Nobilis (2007) conducted a landmark study of changes in the thermal regime of Austrian rivers between 1901 and 2001. Annual mean river temperatures were found to rise by up to +1.5°C over the 20th century and track patterns in the North Atlantic Oscillation index (NAOI, i.e. a large-scale climate diagnostic based on the atmospheric pressure differential between the Icelandic Low and Azores High that is associated with heat and moisture advection across Europe; .g. Jones *et al.*, 1997). Similarly, Hari *et al.* (2006) analysed data for 25 Swiss alpine rivers to find substantial warming over the last quarter of the 20th century, with a step change in 1987 linked to the shift in the NAOI to a highly positive phase. For the East Creek in British Columbia, Canada, Kiffney *et al.* (2002) found the highest winter temperature to occur in El Niño years.

Attribution of warming trends to climate patterns and change is difficult. For example, Kinouchi *et al.* (2007) suggest that warming of spring and winter temperature for central Tokyo from 1978-1998 is related to increases in discharge of heated wastewater, not climate. Petersen & Kitchell (2001) demonstrate that July temperature for the Columbia and Snake rivers in the Pacific Northwest, USA, have not responded to climate shifts but rather increasing dam construction since 1930. Impoundment has been shown also to decrease mid open-water season temperature for the Lena River, Siberia (Yang *et al.*, 2005).

Kelleher *et al.* (2012) investigated controls on the thermal sensitivity of Pennsylvania rivers using linear and non-linear regression and found Strahler stream order and baseflow contribution to be the primary controls. For small streams, baseflow contribution was the primary determinant of sensitivity, with greater contributions from baseflow resulting in decreased sensitivity values; whereas, for large rivers, thermal sensitivity increased with stream size, explained by accumulated heat through the stream network. These findings resonate with other studies reporting the importance of groundwater in buffering climatic sensitivity of river temperature (Erickson & Stefan, 2000; Mohseni *et al.*, 1999; O'Driscoll & DeWalle, 2006). However, small headwater streams are often forested and/ or drain frozen water stores (snowpacks and glaciers) both of which factors also reduce direct climate sensitivity (Caissie, 2006). In contrast to Kelleher *et al.* (2012), other studies have demonstrated weaker air-water temperature associations due to increased thermal capacity and response lag times for larger downstream river reaches (e.g. Webb *et al.*, 2003). Hence, there is some, but no definitive consensus, on moderation by basin properties of river temperature sensitivity to climate-related change/ variability, which suggests site specific context is important.

Thus, it is evident from the international literature that variability in river temperature over the 20th century is a complex, dynamic response to climate patterns and hydrological change moderated by basin properties and anthropogenic impacts. It should be noted also that, although the majority of studies illustrate a warming trend over recent decades, some studies show river cooling (Langford unpublished data cited by Webb *et al.,* 2008; Smith *et al.*, 1995).

For the UK, there are only a handful of long-term water temperature studies that provide very spare national coverage. Water temperature trends in the River Exe basin, Devon, were analysed by Webb & Walling (1992) over a 14-year study period (1977-1990) and revealed rising water temperature to match patterns in air temperature and land use (i.e. removal of riparian shade). The 1975-76 drought distorts analyses of water temperature trends at the end of the 20th century for many UK rivers (Webb, 1996) as the low flows (reduced thermal capacity) and high energy inputs cause river temperature to peak. Such annual variability raises questions about the search to detect linear trends without attribution of causes. Langan *et al.* (2001) analysed a 30-year record for a Cairngorm river and found no significant trend in annual water temperature, but an increase in spring and winter maxima and spring mean water temperature. These increases were attributed to a reduction in spring snowmelt contributions to flow. For mid-Wales, Durance & Ormerod (2007) suggest that forest and moorland river temperature have warmed by +1.5°C and +1.7°C from 1981-2005, respectively, when variation in the NAOI is factored-out.

Probably the longest-term and most spatially widespread assessment of river temperature for the UK is the recent work by des Clers *et al.* (2010), which uses data from the newly compiled Environment Agency Surface Water Temperature Archive (Orr *et al.,* 2010). This archive spans the latter part of the 20th century; and it is limited to England and Wales. There is no national-scale river temperature database for Scotland. The Surface Water Temperature Archive contains over 28,000 records of river temperature but <50% are >10 years long (Figure 2). Most archived data were collected opportunistically during hydrographic or water quality sampling campaigns (des Clers *et al.*, 2010). Figure 3 illustrates the spatial distribution of records of varying lengths in the Environment Agency of England and Wales' Freshwater Temperature Archive. With respect to Environment Agency regions, records of >40 years are limited to the South-West and Wales. For records of 20 years, the spatial distribution is more even but there is a data gap for the Midlands. Sensitivity analysis identifies 18 years (1989-2006) as the optimum time span to maximise spatial network extent across England and Wales (Figure 4). Sampling intervals of data in the Environment Agency's Surface Water Temperature Archive are fortnightly to monthly predominantly; and sampling is daily or continuous at 351 sites only. The mean monthly sampling frequency in all regions, except Wales, is much greater for the earlier period in the record that provides the optimum spatial coverage (Figure 5). In the North-West and Thames regions, the mean monthly sampling frequency is < 2 observations in several years.

des Clers *et al.* (2010) assessed temporal trends using 3,157 sites from the Archive and reported that mean annual water temperatures increased across England and Wales between 1990- 2006 at an average rate of 0.29°C decade^{-1} and that there is evidence of greater warming in the southeast of England and in coastal areas (Figure 6). These results were contextualised by a comparative rise in mean annual air temperature (a proxy for net heat exchange at the air-water interface; Johnson, 2003; Webb *et al.*, 2003) over the same period of 0.2°C decade^{-1}. However, there remains no research on the effects of hydrological and other river basin processes (e.g. land use change) on these observed changes.

As well as providing a basis for evaluating potential temporal trends, the Archive supports tentative inference of factors influencing spatial patterns in river thermal regime across England and Wales. Figure 7 displays summary statistics for mean, minimum, maximum and range of water temperature at 2,832 sites with >250 temperature samples between 1990-2007 (Cooper, 2010; Orr *et al.*, 2010). A common colour scheme is used to map *z*-scores, with blue colours indicating negative *z*-scores (site values < average for England and Wales) and red colours indicating positive *z*-scores (site values > average). These maps begin to reveal possible large-scale controls on river temperature, although much more detailed analysis is necessary. There is some evidence of an altitudinal effect with a general west to east increase associated inversely with topography; and mid-Wales, the Pennines and Dartmoor are cooler than the lower lying Norfolk Fens and Somerset Levels. Minimum temperatures are higher along the south and south-west coast of England, indicating a possible latitudinal influence but this is complicated by a co-varying maritime influence.

WHAT MAY HAPPEN IN THE FUTURE?

Climate change is expected to alter future river thermal regimes (Huguet *et al.*, 2008); however, this is a much under-researched topic with scientific attention growing recently (Webb *et al.*, 2008). Modellers of river temperature under climate change use mainly statistical associations between air and water temperature (e.g. Morrill *et al.*, 2005; studies reviewed below), although a few deterministic heat transport studies have been conducted (Meisner, 1990; Stefan & Sinokrot, 1993; Sinokrot *et al.*, 1995). Notably, analyses of historical records indicate that the strength of air-water temperature relationships increase from sub-daily to monthly resolution, but weaken for annual data

(Webb *et al.*, 2008) because water temperature shows less year-to-year variability than air temperature (Pilgrim *et al.*, 1998; Erickson & Stefan, 2000; Webb *et al.*, 2003).

The most comprehensive work on climate change impacts on river temperature has been conducted in North America. For example, Mohseni *et al.* (2003) projected changes in river temperature for 803 locations across the contiguous USA using a non-linear air-water temperature relationship. Projections were based on air temperature from the Canadian Centre of Climate GCM for a doubling of atmospheric CO_2 concentration. Mean annual stream temperature increased significantly by +3.14 ± 1.68°C, on average, for 764 stations. Maximum weekly temperature increased significantly by +2.24 ± 1.88°C, on average, at 399 stations. Minimum weekly stream temperature increased significantly by +2.25 ± 1.14 °C, on average, at 455 stations. In terms of geographical patterns, greater maximum weekly river temperature increases were observed in the southern than the northern USA. In a continental European study (Danube at Linz, Austria), Webb & Nobilis (1994) predicted an increase in monthly mean river temperature of +1.2-2.1°C for an air temperature increase of +2.3-3.4°C and a 15% reduction in flow between June-September by2030.

At the global scale, van Vliet *et al.* (2011) tested the performance of a non-linear water temperature model (modified from Mohseni *et al.*, 1998, by using daily air temperature and river flow as predictors) for 157 river stations from 1980-1999. Using river discharge as an input variable improved predictive power at >87% of stations (cf. air temperature alone), particularly during heat-wave and low flow conditions, at stations with high winter discharges and low summer discharges, and for large rivers. Inclusion of discharge yielded modest increase in model performance for stations influenced by reservoirs or snowmelt. Sensitivity analysis indicated increases in annual mean temperature of +1.3°C, +2.8 C and +3.6°C under air temperature increases of +2°C, +4°C and +6°C respectively. Discharge decreases of -20 %and -40% increased annual mean water temperatures by +0.3°C and +0.8°C on average, respectively; while a discharge increase of +20% reduced annual mean water temperatures by -0.2°C on average. Importantly, an increase in air temperature of +4°C combined with a decrease in discharge of -40% resulted in a greater increase in river temperature than an increase in air temperature of +6°C alone, which emphasises the importance of considering hydrological as well as climate change.

For the UK, there are very, very few predictive modelling studies of river temperature under climate change. Hence, there is scant evidence to evaluate what may happen to UK river temperature in the 21st century. At 36 UK river sites, Webb & Walling (1992) modelled a rise of +1-3.6°C in monthly mean water temperature by 2050, given a scenario of monthly mean air temperature increase of+2-3°C. The magnitude of increase was dependent on geographical location and river basin characteristics, with greater groundwater contributions and forest cover modulating responsiveness to climate change. Subsequently, Webb & Walsh (2004) modelled 27 UK river monitoring sites by incrementing present conditions (defined by applying air-water temperature relationships to a baseline annual cycle of weekly mean air temperature averaged over >5 years of record) for air temperature increases predicted by low and high warming UKCIP02 scenarios for 2020, 2050 and

2080. Results indicate that warming will be modest to very significant depending on the scenario applied; and warming will be moderated by site and basin characteristics. A comparison of four UK rivers revealed the importance of groundwater in moderating river temperature response to climate change with surface water-fed rivers on non-calcareous lithology more responsive (+1.8-3.6°C) than spring-fed, chalk rivers (+1.1-2.2°C) to an increase of +2-4°C in monthly mean air temperature (Mackey & Berrie, 1991).

There is much uncertainty over river temperature change because responses may vary widely across large geographical areas and future water temperature predictions depend on the climate scenario applied (Cooter & Cooter, 1990; Webb & Walsh, 2004). Furthermore, climate change will alter hydrology (surface water and groundwater flows) and basin/ site characteristics (e.g. riparian vegetation), and so moderate river temperature (Morrison *et al.*, 2002). Consequently, the spatial patterns in future river temperature may differ from those projected for driving climate variables (e.g. Webb & Walsh, 2004). Simple air-water temperature associations, especially when air temperature is taken from sites distant from the river basin of interest, may lead to poor future predictions due to failure to capture local controls. As well as spatial differences, river temperature responses may vary seasonally with research in the north-central USA suggesting spring-summer warming may be less marked than autumn cooling (Stefan and Sinokrot, 1993). These seasonal shifts may reflect future change in influential climatic variables, (see UNDERSTANDING CONTROLS), and/ or seasonal contrasts in the sensitivity of rivers to the effects of climate change (Webb *et al.*, 1996).

CONFIDENCE IN THE SCIENCE

This section evaluates the confidence in the science reviewed in the previous two sections qualified using the confidence and likelihood terms for the Intergovernmental Panel on Climate Change (IPCC) 5th assessment report (AR5): http://www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf

As explained above, it is not possible to make definitive statements about the direction, magnitude, rate and significance of changes in UK river water temperature over the 20th century and possible changes over the 21st century due to uncertainties in:

- historical river temperature data with respect to (ir)regularity of sampling, variable time spans of different authors' analyses, and limited spatial coverage of the UK
- attributing historical river temperature patterns to climate factors as opposed to other drivers of change
- future climate scenarios
- future hydrological scenarios
- future land use scenarios
- future actions of water managers, politicians and others

- future interactions and feedbacks between climate, hydrological, land use and management scenarios
- translation of climate change effects to river temperature impacts, which will be moderated by other drivers of change

The following statements focus on the UK evidence base and are tempered by above uncertainties.

Confidence in the science on WHAT HAS HAPPENED?

- *Medium level of agreement* on the influence of climatological, hydrological, land-use and anthropogenic controls on UK river water temperature.
- *Medium level of agreement* and *as likely as not* that UK river temperature has increased over the latter of the 20th century
- *Low agreement* on the attribution of UK river temperature changes over the latter of the 20th century to drivers of change, in particular climatic warming.

Confidence in the science on WHAT MAY HAPPEN IN THE FUTURE?

- *Medium level of agreement* and *as likely as not* that UK river temperature will increase in the 21st century; however, there are a number of interlinked sources of uncertainly (above) that mean estimating rates of river temperature change for sites across the UK is beyond current knowledge.

For all these statements above, limited evidence is available for the UK. Some support for UK findings is provided by the international literature reviewed herein.

KNOWLEDGE GAPS

A number of priority knowledge gaps are emergent from this Technical Report. Addressing the following research needs will improve understanding of past, contemporary and future river temperature change in the UK:

- UK monitoring network to collect long-term records with nested spatial coverage and including benchmark near-natural river basins
- Metadata to provide information on site specific conditions that influence river temperature
- Robust analysis of existing UK data (including collation of data from sources not currently in the Environment Agency Surface Water Temperature Archive) to detect river temperature change and avoid confounding effects of inconsistencies in sampling resolution, length of time-series, and spatial bias in site locations
- Better understanding of space and time scales of river thermal heterogeneity
- Systematic attribution of river temperature patterns to drivers of change
- Quantification of river temperature sensitivity to drivers of change, including comprehensive assessment of climatic sensitivity

- Improved future projection of river temperature change accounting of sources of uncertainty (see CONFIDENCE IN THE SCIENCE)

SOCIO-ECONOMIC IMPACTS

This section identifies the socio-economic impacts of changes in UK river water temperature. Water temperature influences the growth and performance of aquatic organisms (Elliott, 1991; Gurney *et al.*, 2008; Malcolm *et al.*, 2008) and their distribution (Vannote *et al.*, 1980; Ebersole *et al.*, 2001; Caissie, 2006). Hence, changing river water temperature has potential implications for fisheries management and aquaculture (Caissie, 2006; Webb *et al.*, 2008), especially in the UK where salmonid fisheries are of major economic importance (North, 1980). Less well documented are the effects of changing water temperatures on industrial processes. Over 90% of the electricity supplied in the UK is generated in thermal power stations that is coal, gas and nuclear (Department of Energy & Climate Change, 2011), for which river water at low temperature is essential to cool the condensers of steam turbines (Clark & England, 1963). The proportion of electricity to be generated by thermal power stations is to be reduced to by 2020; but these stations will still represent ~60% of total power supply in the UK (Department of Energy & Climate Change, 2011). Elevated river temperature regimes will affect the utility of current drinking water treatment processes and, in turn, their energy requirements (Soh *et al.*, 2008). Understanding, with a high level of confidence, how river temperature dynamics will change during the 21st century is vital for the socio-economic activities identified herein.

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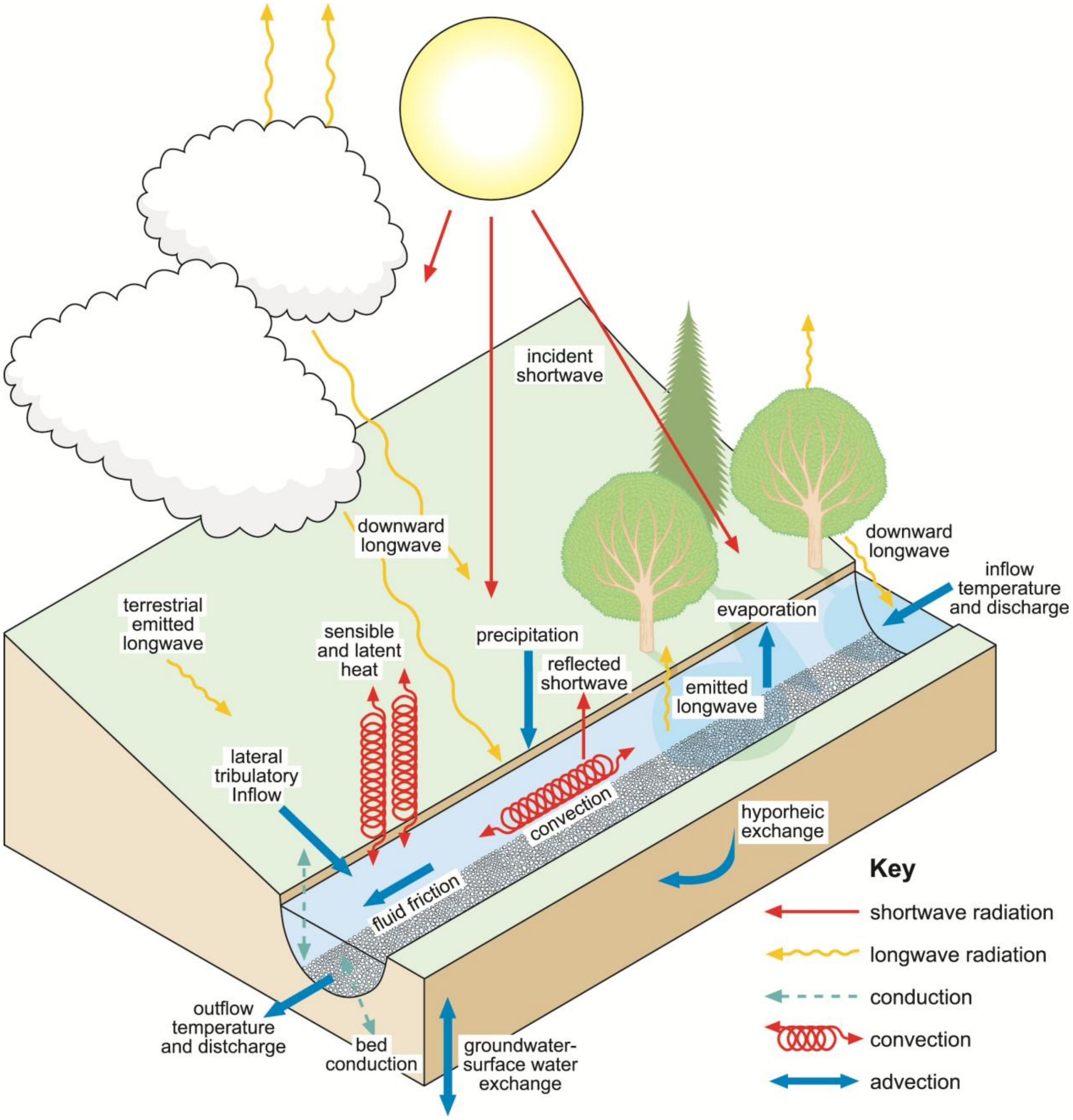

Figure 1. A schematic representation of the energy and hydrological fluxes controlling river water temperature (Hannah *et al.*, 2008).

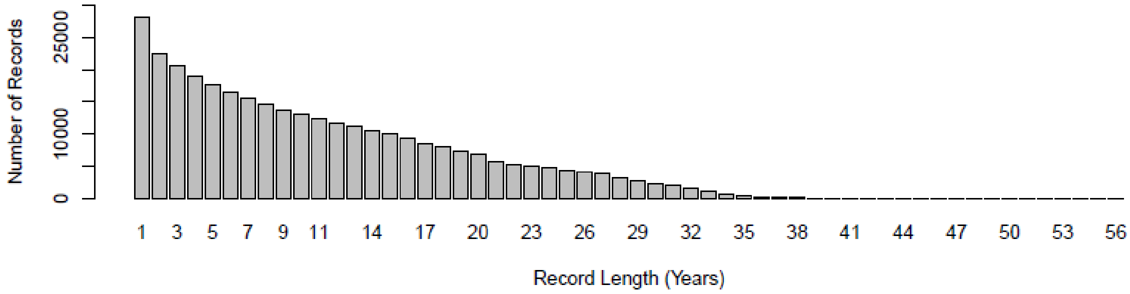

Figure 2. Length of records (years) for sites in the Environment Agency of England and Wales' Freshwater Temperature Archive.

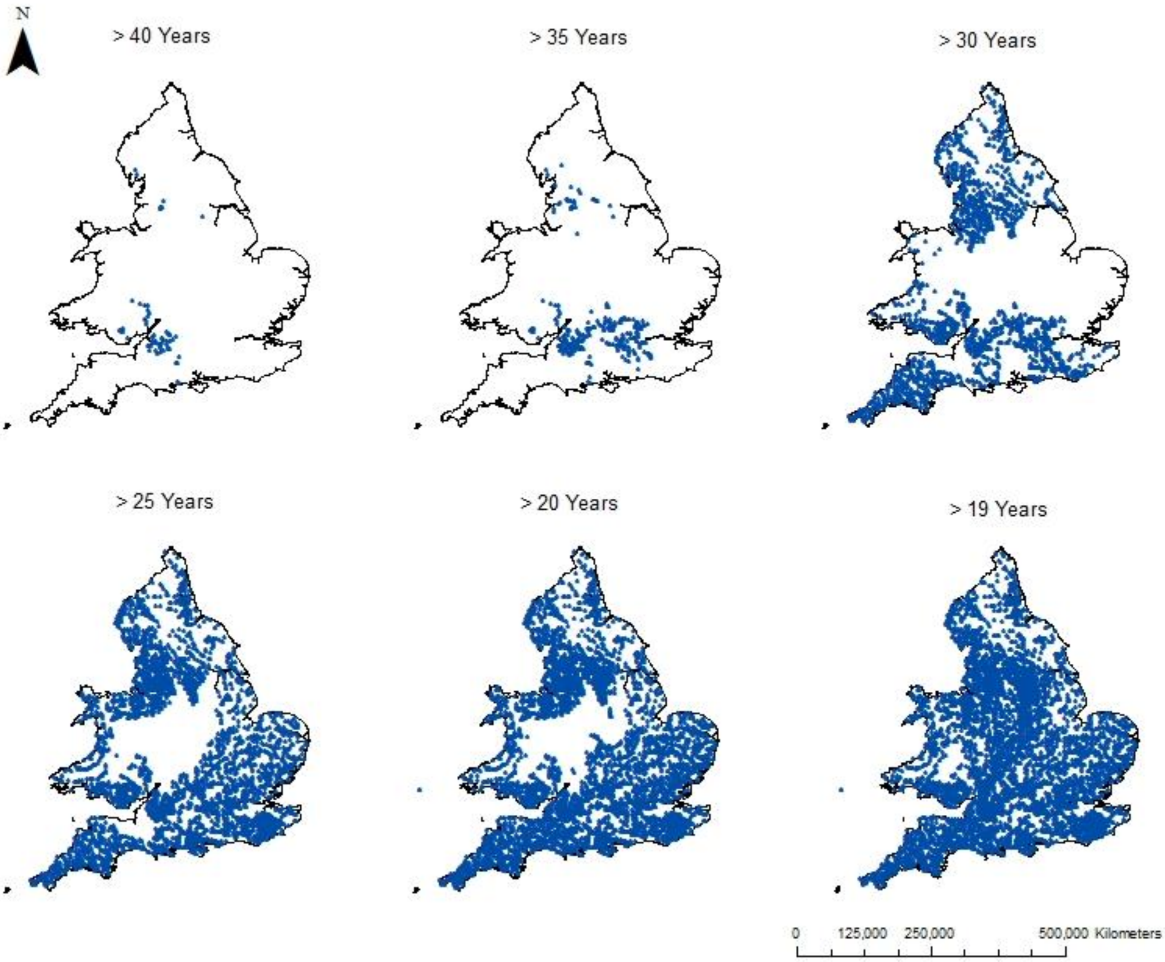

Figure 3. Spatial distribution of record of varying lengths in the Environment Agency of England and Wales' Freshwater Temperature Archive.

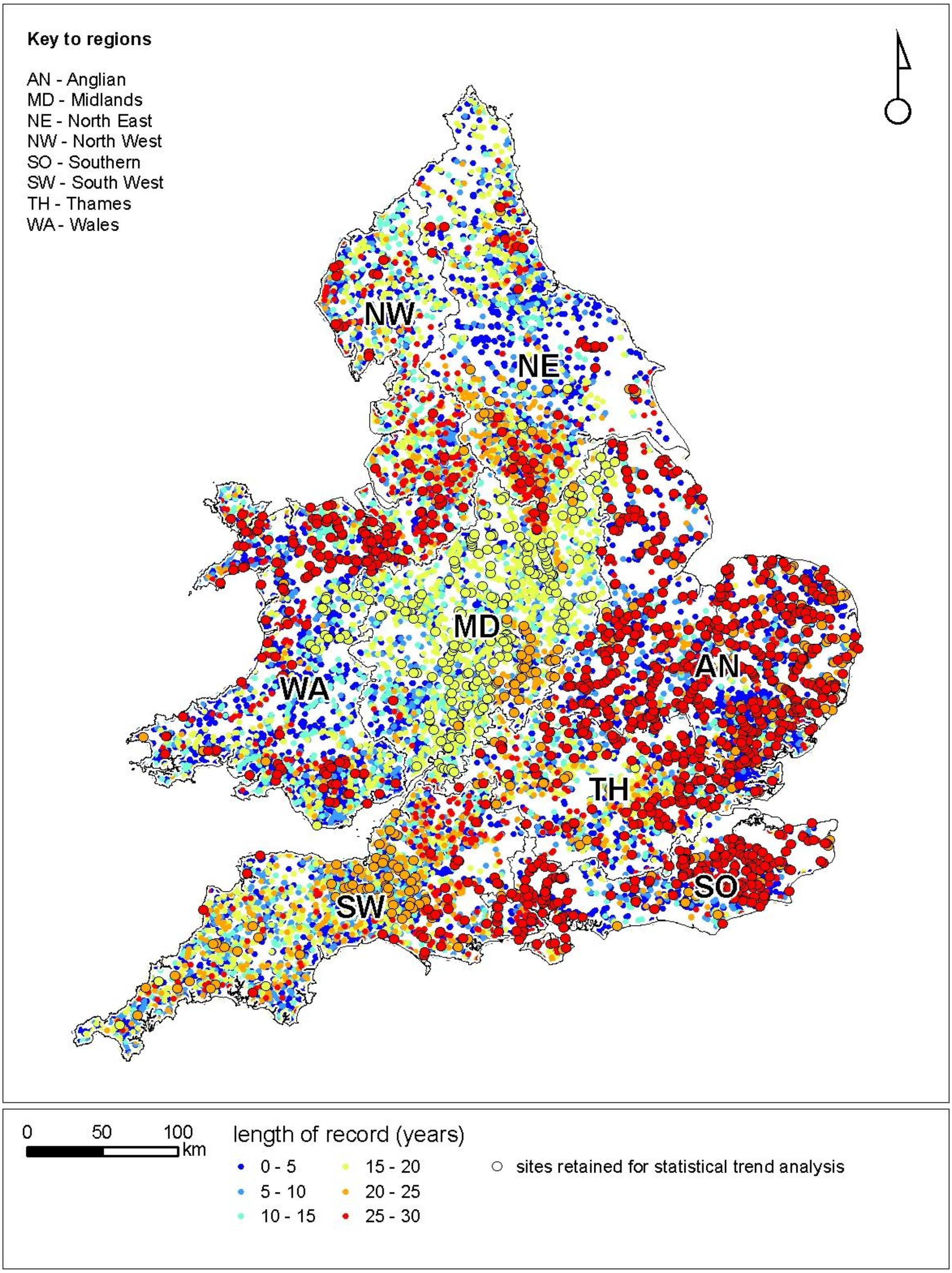

Figure 4. Distribution of river water temperature monitoring sites in Environment Agency of England and Wales' Freshwater Temperature Archive by Environment Agency regions (from des Clers *et al.*, 2010).

[Environment Agency regions: NW = North West; NE=North East; MD=Midlands; WA=Wales; TH=Thames; SO=Southern; SW=South West; AN=Anglian. Colour key illustrates record length. Large circles denote sites where temporal trends (1990-2006) were assessed.]

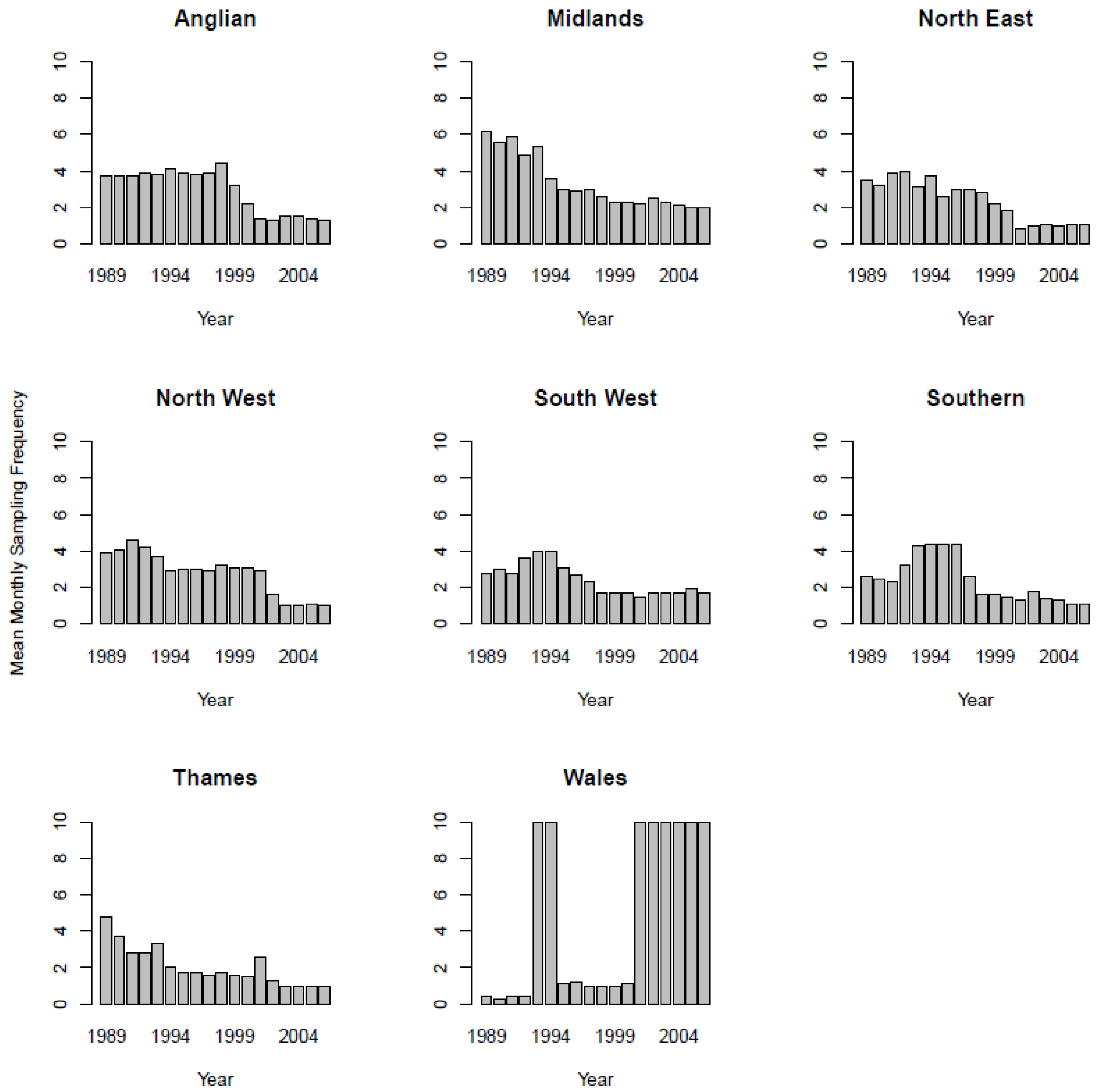

Figure 5. Environment Agency of England and Wales' Freshwater Temperature Archive mean monthly sampling frequency (1989-2006) by Environment Agency region.

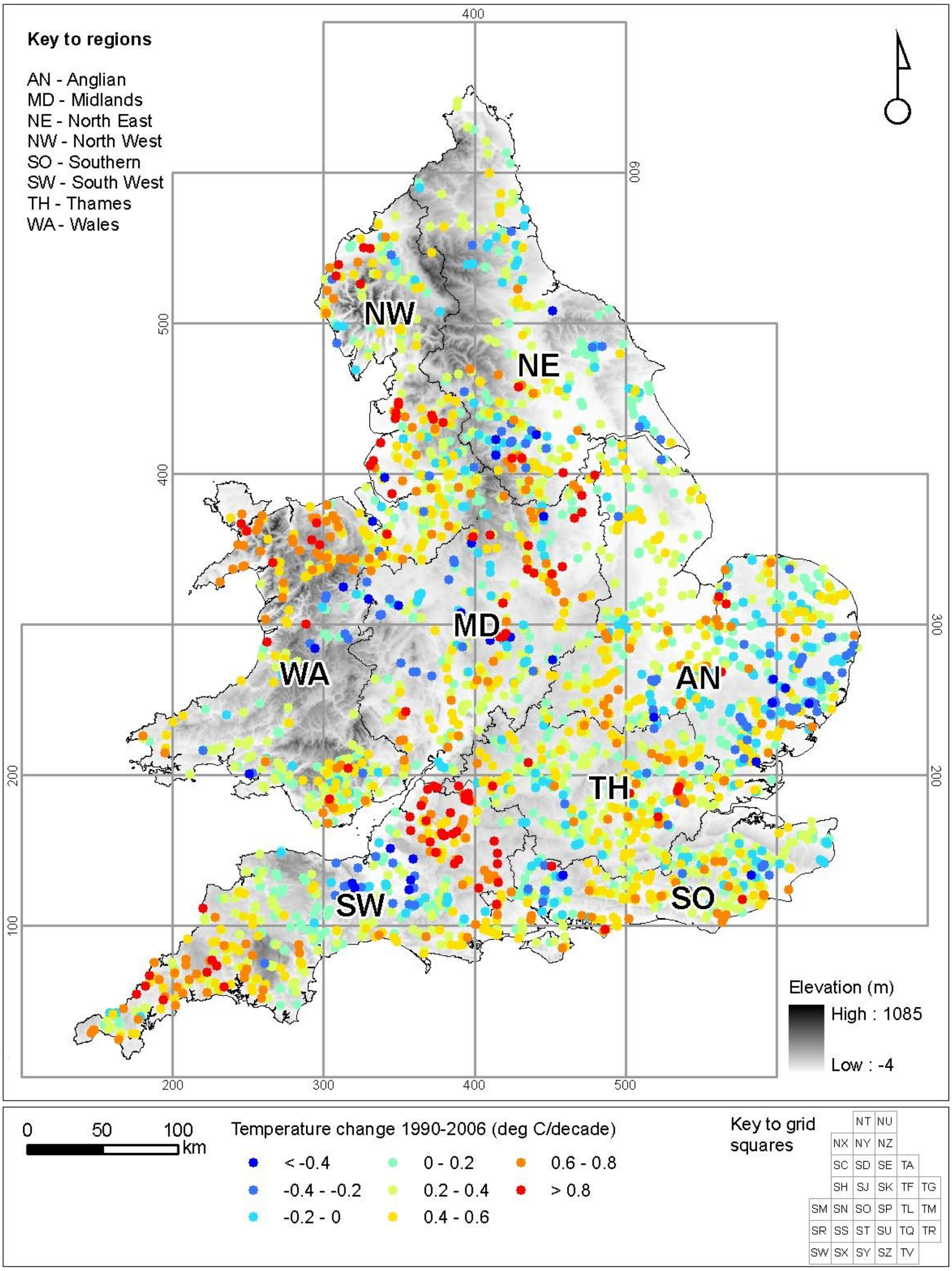

Figure 6. Estimated mean annual river temperature change (°C decade $^{-1}$) using 3,157 sites from Environment Agency of England and Wales' Freshwater Temperature Archive(from des Clers *et al.*, 2010).

[Environment Agency regions: NW = North West; NE=North East; MD=Midlands; WA=Wales; TH=Thames; SO=Southern; SW=South West; AN=Anglian]

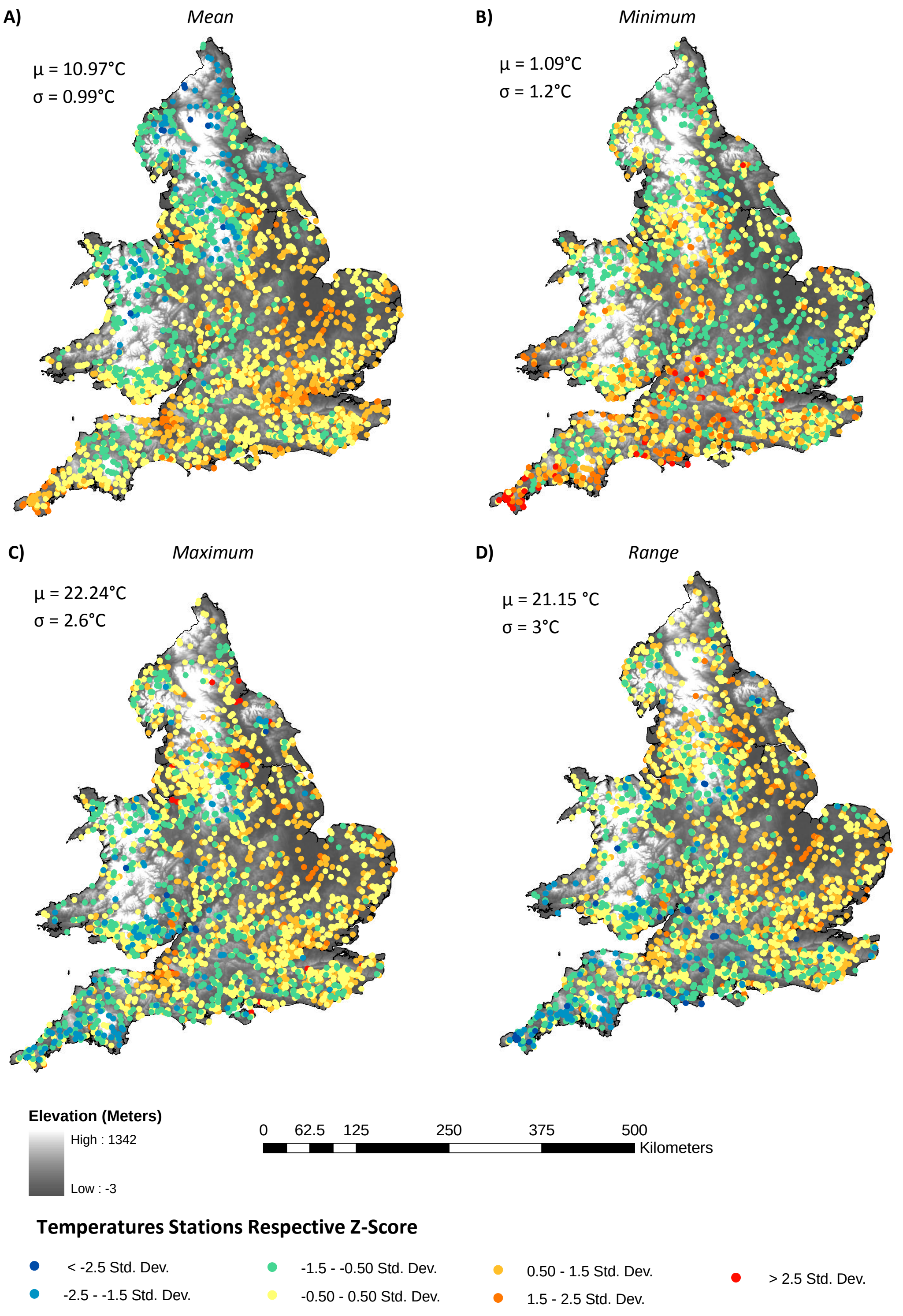

Figure 7. Maps of A) Mean, B) Minimum, B) Maximum and D) Range in water temperature for 2832 sites with >250 samples between 1990-2007 from Environment Agency of England and Wales' Freshwater Temperature Archive (from Cooper, 2010; Orr *et al.*, 2010).

[For each variable, the England and Wales mean (μ) and standard deviation (σ) are provided as text; and each site is colour-coded by z-scores (blue for negative site z-values, below the England and Wales average; red for positive site z-values, above the average).]

Table 1. WHAT HAS HAPPENED? Research on river temperature in the UK.

Author	**Study Scale & Location**	**Study Length**	**Key Findings**	**Controls & Processes**
POINT-SCALE HEAT FLUXES CONTROLLING RIVER TEMPERATURE				
Webb & Zhang (1997)	11 sites in River Exe basin, Devon, southwest England	495 days across 18 study windows	Averaged over the entire dataset non-advective energy gain contributions = net radiation (56%), friction (22%), sensible heat (13%), condensation (6%) and bed heat flux (3%). Non-advective energy loss contributions = net radiation (49%), evaporation (30%), sensible heat (11%) and bed heat flux (10%). Magnitude and relative importance of heat fluxes varied in time and space.	Chanel morphology, valley topography, riparian vegetation, substratum composition hydrological conditions, and river regulation influence variability and magnitude of heat fluxes over time and between sites.
Evans *et al.* (1998)	1 site in English Midlands	8 days	On average, over 82% of the total energy transfers occurred at the air-water interface with 15% at the channel bed-water interface. Heat exchange at the channel bed varied considerably (max. 24%) in response to varying bed thermal, and periphyton and macrophyte cover.	Temporal heterogeneity in bed heat flux caused by varying riverbed albedo (due to seasonal changes in periphytion, macrophyte and silt cover) and relative contribution of surface- vs. ground-water.

Table 1. Continued

Author	Study Scale & Location	Study Length	Key Findings	Controls & Processes
POINT-SCALE HEAT FLUXES CONTROLLING RIVER TEMPERATURE (CONTINUED)				
Webb & Zhang (1999)	1 site in River Exe basin, southwest England	1 year	Net radiation contributed ~90% of energy gains during summer months. Sensible heat enhanced during summer. Bed heat flux reduced considerably at 1 site where weed growth extensive.	Sensible heat transfers enhanced in groundwater-fed streams during summer due to their lower water cf. air temperature. Macrophytes (lower thermal conductivity cf. sediment) decrease bed heat fluxes.
Hannah *et al.* (2004)	1 site, Cairngorms, northeast Scotland	7 months (autumn-spring)	Streambed (atmosphere) dominant energy source (sink) for heating (cooling) channel water	Groundwater upwelling advects heat into the bed. Friction important heat source in winter. Sensible heat primary atmospheric heat source when radiative transfers limited.
Webb & Zhang (2004)	4 sites in River Exe basin, southwest England	1 year	Sensible heat source (sink) in summer (winter). Bed heat sink (source) in summer (winter). Friction heat source. Evaporation heat sink. Differences between forested and non-forested sites, especially in terms of radiation.	Forest canopy reduces shortwave-radiation. Tree trunks and branches in deciduous forests cause shading effects even during winter.
Hannah *et al.* (2008b.)	1 open moorland and 1 semi-natural forest site,	2 years	Net radiation greater summer (less winter) for moorland cf.	Forest canopy shades in summer (but offsets net radiation

	Cairngorms, northeast Scotland		forest. Magnitude and variability of turbulent fluxes greater for moorland cf. forest	loss in winter due to longwave emission) and sheltering effects on sensible and latent heat

Table 1. Continued

Author	Study Scale & Location	Study Length	Key Findings	Controls & Processes
REACH-SCALE TEMPERATURE VARIABILITY IN THE WATER-COLUMN AND RIVERBED				
Carling *et al.* (1994)	channel cross-sections, River Severn	< 1 day	Water temperature in dead zones of meanders 2°C warmer cf. flowing main channel	Shallower, slower flowing water warms more rapidly than deeper, faster flowing thalweg (i.e. atmospheric equilibration time)
Clark *et al.* (1999)	202 channel cross-sections, River Frome and Bere Stream, southwest England	< 1 day	0.2 -0.4°C vertical and/ or horizontal temperature contrasts across 78% of channel cross-sections	
Hannah *et al.* (2009)	Riffle-pool sequence, River Tern, English Midlands	22 months	Hyporheic temperature cooler (warmer) than water column in summer (winter), with convergence in spring and autumn. Temperature varies across and between riffles	River geomorphology alters groundwater-surface water interactions, hence thermal dynamics
Krause *et al.* (2011)	Riffle-pool sequence, River Tern, English Midlands	9 months (summer-winter)	Streambed temperature variability 0.75°C (3°C) over 16 m (0.4 m) longitudinally (vertically)	

Table 1. Continued

Author	Study Scale & Location	Study Length	Key Findings	Controls & Processes
FOREST EFFECTS ON RIVER TEMPERATURE				
Crisp (1997)	5 sites in 2 catchments, upper-Severn, mid-Wales (2 sites pre-clear-felled; 3 sites post-clearfelled)	15-52 months	Mean annual water temperature reduced by 0.4 °C and daily range lower pre-clearfelling. Greatest effects in summer.	Forest canopy reduces spring and summer water temperature, and elevates winter temperature (cf. openly situated sites)
Weatherley & Ormerod (1990)	6 sites across clearfelled and afforested locations, upper River Severn, mid-Wales	1-2 years	Mean daily water temperature lower (higher) in forest cf. moorland in spring and summer (winter).	
Crisp (1997)	5 sites under clearfelled and coniferous forest, upper River Severn, mid-Wales	1-4 years	Mean annual water temperature reduced by 0.4 °C for clearfelled sites	
Stott & Marks (2000)	1 site pre-clearfelling and 1 site post-clearfelling, River Severn, mid-Wales	28 months	Monthly mean temperature increased by 7°C in July and 5.3°C during August post-clearfelling.	
Malcolm *et al.* (2004b)	5 sites situated in open moorland and one in mixed (deciduous, coniferous) woodland	3 years	Riparian woodland reduced diurnal variability and extremes of temperature.	
Malcolm *et al.* (2008)	2 sites situated in open moorland sites and three sites in mixed	35 months	Under forest: amplitude of annual temperature regime reduced, daily mean	

	woodland		and maximum decreases, in daily minimum increases, and diurnal variability reduced	

Table 1. Continued

Author	Study Scale & Location	Study Length	Key Findings	Controls & Processes
FOREST EFFECTS ON RIVER TEMPERATURE (CONTINUED)				
Broadmeadow *et al.*, (2011)	14 forested and 4 open-moorland sites in 2 catchments, New Forest, Southern England	3 years	Largest differences between forested and open sites during summer. Effects observed at canopy shading of 20-40%.	

Author	Study Scale & Location	Study Length	Key Findings	Controls & Processes
SPATIAL AND TEMPORAL DYNAMICS ACROSS RIVER NETWORKS				
Webb & Walling (1992)	3 sites on tributaries with contrasting land use, River Exe basin, southwest England	14 years	Significant increase in water temperature 0.05 to 0.092 °C y^{-1} associated with air temperature increases and removal of riparian vegetation shading	Climate and land use/ land cover influence long-term water temperature trends
Crisp *et al.* (1982)	7 streams (two watercress beds) in southern England	1-8 years	Surface water fed streams lower annual mean but greater cycle amplitude cf. groundwater fed streams.	Increased groundwater inputs, longer hydrological residence times and increased thermal capacity (flow volume) buffer influence of climate on water temperature
Webb & Walling (1986)	17 sites in River Exe basin, southwest England	5 years	Thermal variability buffered for larger basins areas and by longer hydrological residence times	
Webb *et al.* (2003)	Four sites draining basins of contrasting area,	5 years	Air-water temperature relationships weaken	

	River Exe basin, southwest England		with increased thermal capacity and longer residence times	

Table 1. Continued

Author	Study Scale & Location	Study Length	Key Findings	Controls & Processes
SPATIAL AND TEMPORAL DYNAMICS ACROSS RIVER NETWORKS (CONTINUED)				
Hrachowitz *et al.* (2010)	25 sites, River Dee, northeast Scotland	2 years	Small, non-forested, inland, upland sites most sensitive to air temperature. Large, forested, lowland sites least sensitive air temperature.	See above
Imholt *et al.* (in press)	26 sites across nested scales, River Dee, northeast Scotland	2 years	Least spatial variability at the sub-reach scale (0.3 °C difference between riffles and pools) with greatest variability between tributaries (8.1°C difference in diurnal range) and sub-catchments.	Thermal variability scale-dependent and related to river morphology, land use, altitude and forest cover. Notably, similar thermal patterns may be driven by different sets of physical controls.