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# Recent advances in stream and river temperature research

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## Abstract:

Research on stream and river temperatures is reviewed with particular attention being given to advances in understanding gained since 1990 and on investigations of fundamental controls on thermal behaviour, thermal heterogeneity at different spatial scales, the influence of human impacts and the nature of past and future trends. Copyright © 2008 John Wiley & Sons, Ltd.

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## INTRODUCTION

The study of river water temperature has a long history, and in Europe, for example, dates back to measurements made on the River Nile by Coutelle during the Napoleonic expedition to Egypt between 1799 and 1801. An interest in the formation of ice on major navigable inland waterways (Smith, 1972) prompted the establishment of systematic monitoring of river temperature in countries such as Austria in the late 19th Century (Webb and Nobilis, 1995), by which time the thermal behaviour of flowing waters in Central Europe was the subject of scientific investigation (Forster, 1894). During the 20th Century, water temperature studies developed within the framework of several academic disciplines in North America, Europe and Japan, although investigations of thermal influences on stream ecology and the impact of heated effluent discharges into larger rivers, often in an engineering context, represented two major themes in the period up until the early 1970s (Smith, 1972). Progress in understanding the temperature of streams and rivers has been the subject of three previous general reviews. Smith (1972) charted studies undertaken since the turn of the 20th Century to determine the physical basis of water temperature in unpolluted rivers and to evaluate the role of different human activities in generating thermal pollution. Ward (1985) discussed available data on thermal conditions prevailing in the lotic ecosystems of the southern hemisphere and, in doing so, summarized existing knowledge on factors controlling stream and river temperatures, the nature of thermal regime and the role of human modifications. Most recently, Caissie (2006) has reviewed the literature to describe the factors and underlying physical processes related to river temperatures, to provide a general overview of water temperature models, and to discuss natural and human-modified thermal conditions and their potential implications for aquatic habitats.

It is clear from these reviews that temperature is an important physical property of flowing waters because of its enormous significance for all freshwater organisms (e.g. Farrell and Rose, 1967; Fry, 1967; Anderson, 1969; Patrick, 1969; Langford, 1990; Ward, 1992; Elliott, 1994); its influence on other aspects of water quality, such as dissolved oxygen and suspended sediment concentration (e.g. Lane *et al.*, 1949; LeBosquet and Tsivoglou, 1950); its economic importance, for example, in water requirements for industry, agriculture, aquaculture and recreation (e.g. Clark and England, 1963; Raney, 1963; North, 1980; Langford, 1983); and its sensitivity to both natural and human factors (Walling and Webb, 1981, 1992; Webb, 1996a). In many countries, temperature has traditionally received much less attention than other facets of water quality, such as suspended sediment behaviour and hydrochemistry. However, recent years have witnessed a renewed interest in the thermal behaviour of flowing waters, which reflects a number of factors.

Firstly, technological developments have facilitated the measurement and monitoring of stream and river temperatures. The advent of programmable digital data loggers, that may be downloaded in the field or interrogated remotely through various telecommunication systems, has removed many of the problems associated with earlier recording thermometers based on paper charts, punch-paper and magnetic tape and the first

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devices using solid-state memory (Herschy, 1971; Stevens *et al.*, 1975; Cunningham, 1984), and also has made redundant concerns about the representativeness of temperature statistics calculated from relatively infrequent observations (Crisp, 1990a; Preud'homme and Stefan, 1992). Particularly, the arrival of low-cost, accurate and reliable miniature temperature recorders has been a boon to researchers and statutory authorities seeking to investigate temperature behaviour at multiple sites (Johnson, 2003) and in particular applications, such as the documentation of groundwater–surface water interactions (e.g. Johnson *et al.*, 2005). However, problems relating to maintaining and calibrating recorder networks remain (Bartholow, 1989; Lewis *et al.*, 2000). Intensive manual field surveys may still be required to supplement data from monitoring networks (e.g. Booth, 2002), but the potential for using remotely sensed thermal infrared (TIR) imagery for documenting spatial variability in river temperatures is being increasingly realized (e.g. Torgersen *et al.*, 2001; Faux and Archibald, 2003; Cherkauer *et al.*, 2005; Loheide and Gorelick, 2006). Data may be collected from TIR sensors mounted on satellite, aircraft and ground-based platforms, and the accuracy, uncertainties and problems associated with spatial resolution, calibration, georeferencing, temperature sampling and image interpretation, for example, are being identified and addressed (Faux *et al.*, 2001; Larson *et al.*, 2002; Beschta *et al.*, 2003; Kay *et al.*, 2005; Handcock *et al.*, 2006).

The development of new techniques of data analysis and modelling has provided a second stimulus for new research on stream and river temperatures. Many different approaches of varying sophistication have been developed to model different aspects of thermal behaviour in space and in time (Moore, 2005; Caissie, 2006). These have included empirical models that rely on statistical analysis to make predictions from weather data or information on catchment characteristics (e.g. Stoneman and Jones, 1996; Donato, 2003; Neumann *et al.*, 2003; Rivers-Moore and Lorentz, 2004; Benyahya *et al.*, 2007), and physically based modelling that involves solving the heat budget equation (Wang and Martin, 1991; Sinokrot and Stefan, 1993; Kim and Chapra, 1997; Foreman *et al.*, 2001; Caissie *et al.*, 2007). The latter approach has been applied to individual reaches and at the scale of the stream network or whole catchment, and for making predictions under steady-state and transient-flow conditions (e.g. Sullivan *et al.*, 1990; Bartholow, 1991; Bravo *et al.*, 1993; Rutherford *et al.*, 1997; Chen *et al.*, 1998a,b; Polehn and Kinsel, 2000; Younus *et al.*, 2000; St-Hilaire *et al.*, 2003; Cox and Bolte, 2007). Furthermore, many advances in modelling have come through the need to assess, understand and mitigate human impacts on thermal behaviour in water courses (e.g. Lence *et al.*, 1992; Mitchell *et al.*, 1995; Foreman *et al.*, 1997; LeBlanc *et al.*, 1997; Bradley *et al.*, 1998; Gu *et al.*, 1999; Mitchell, 1999; Wright *et al.*, 1999; LeBlanc and Brown, 2000; St-Hilaire *et al.*, 2000; Gu and Li, 2002; Sridhar *et al.*, 2004; Haag *et al.*, 2005). Recent studies have developed and refined earlier approaches to modelling, such as the application of stochastic techniques, to account for the deviations of water temperature from seasonal trends defined by harmonic analysis (e.g. Caissie *et al.*, 1998, 2001) and the use of equilibrium temperature concepts (e.g. Bogan *et al.*, 2004; Caissie *et al.*, 2005). New approaches have also evolved recently. These have included application of geostatistical metrics and the analysis of temporal covariance structures for the prediction of stream temperatures in the Beaverkill Watershed of the Catskill Mountains, New York, USA (Gardner *et al.*, 2003; Gardner and Sullivan, 2004), the use of wavelet analysis to quantify the effects of multi-purpose dams in the Willamette River Basin, Oregon, USA in reducing water temperature variability at multiple time scales from 1 to 8 days (Steel and Lange, 2007), and the estimation of stream temperature characteristics for Turkish water courses using artificial neural networks (Karaçor *et al.*, 2007; Sivri *et al.*, 2007) and for an Exmoor river in South–West England using evolutionary polynomial regression (Giustolisi *et al.*, 2007). Questions of uncertainty in water temperature modelling have also been addressed recently (e.g. Bartholow, 2003).

The need to understand the impacts of human activities, such as power generation, forestry and agricultural practices, impoundment and urbanization, has been a long-standing and continuing motivation underlying many studies of stream and river temperatures (e.g. Titcomb, 1926; Greene, 1950; Brown and Krygier, 1970; Pluhowski, 1970; Hopkins, 1971; Crisp, 1972; Langford, 1972; Hill, 1976; Parrish *et al.*, 1978; Smith, 1979; Stanford and Ward, 1979; Petts, 1986; Beschta and Taylor, 1988; Jankovic, 1990). However, further recent impetus to investigations of human impacts on water temperatures has come from the identification of climate change, particularly associated with anthropogenically induced global warming, as a major potential future influence on river systems (e.g. Cooter and Cooter, 1990; Meisner, 1990; Stefan and Sinokrot, 1993; Arnell, 1996; Cushing, 1997).

The aim of the present article is to set the scene for this special issue of *Hydrological Processes* by reviewing recent research on stream and river temperatures in order to identify current interests, advances in understanding and potentially profitable directions for future studies. The review will concentrate on the works published since 1990, but will not deal with biological aspects of lotic thermal regimes, nor with the modelling of stream and river temperatures, because these topics have been reviewed recently elsewhere (e.g. Caissie, 2006) and are not the focus in the special issue.

## UNDERSTANDING FUNDAMENTAL CONTROLS

Recent studies have extended pioneering field experiments (e.g. Brown, 1969; Pluhowski, 1970) undertaken to determine the nature of the heat fluxes that fundamentally control stream and river temperatures. Webb and

Zhang (1997, 1999) reported the results of measurements of non-advective heat fluxes made on 866 days across 17 sites located mainly in South–West England, and also in other parts of the UK. This work showed that, on an average, radiative fluxes accounted for more than 70% of heat inputs, but the friction of the water with the bed and the banks (15·8%) and sensible heat transfer from the atmosphere (10·3%) were also significant sources of heat energy. The main non-advective outputs of heat were recorded as net radiation (36·8%), evaporation (33·3%), bed conduction (16·3%) and sensible heat transfer to the atmosphere (13·6%). However, the nature of stream heat budgets may also vary significantly in different climatic environments, and studies of the Von Guerard Stream in the Fryxell Basin, Antarctica, for example, have shown that net radiation accounted for 99% of the warming of glacial meltwater flowing through an experimental reach in a polar desert environment, where evaporation, convection and conduction contributed 30, 25–31 and 19–37%, respectively of the non-radiative heat losses (Cozzetto *et al*., 2006). At a much more local scale, the absolute and relative magnitude of heat budget components may be influenced by valley and channel morphology, including changes in channel shape and orientation over very short distances, through the effects of these factors on the exposure of the water course to insolation and to wind (Webb *et al*., 1995).

The presence of a forest canopy has long been known to modify the amount of solar radiation and other meteorological factors influencing stream temperatures (e.g. Pluhowski, 1972; Moore *et al*., 2005a), but the different nature of the heat budget affecting streams in forested catchments has been explored in more detail in recent years. In a novel experiment involving artificial shading of a 200-m reach in Watershed 3 of the H.J. Andrews Experimental Forest, Oregon, USA, Johnson (2004) demonstrated, for conditions at midday in July, that an open reach under full sun experienced a net energy gain of 580 $\mathrm{Wm^{-2}}$ but a reach under full shade had a net loss of 149 $\mathrm{Wm^{-2}}$. Low wind speed and lack of ventilation have been found to limit sensible and latent-heat exchanges over small streams under an intact forest cover (e.g. Story *et al*., 2003), but these exchanges were also estimated to be an order of magnitude lower than the net radiation for headwater streams on sunny days in recent clear-cuts within the Malcolm Knapp Research Forest of coastal British Columbia, Canada, where the effects of bank sheltering in narrow, incised channels are significant (Moore *et al*., 2005b).

In addition to heat transfers at the air–water interface, recent attention has also focused on the nature and importance of energy exchanges at the interface between the water column and the river bed and banks. The importance of these heat fluxes compared with exchanges at the air–water interface has been shown to vary in water courses of different characters. Upto 30% of the heat exchange affecting the water column in the Girnock Burn of the Cairngorms in Scotland occurs at the bed during the winter half of the year (Hannah *et al*., 2004), and Moore *et al*. (2005b) have estimated bed heat conduction to be approximately 10% of net radiation in an open step-pool stream under sunny conditions. Evans *et al*. (1998) suggested that approximately 15% of the energy exchange occurred at the bed in the regulated River Blithe, central England. The nature of energy exchanges at the river bed reflects the net effect of radiative, conductive, convective and advective processes that vary in their importance from site to site. Surface–sub-surface exchanges of water have also been recognized as significantly influencing the heat budgets of small streams. Story *et al*. (2003) showed that groundwater inflow was responsible for about 40% of an approximately 3 °C gross cooling effect in the daily maximum temperature as a small stream in the central interior of British Columbia passed from an open into a shaded reach, while O'Driscoll and DeWalle (2006), in a study of a karstic area in central Pennsylvania, USA, demonstrated that, compared to a water course with negligible groundwater inputs, a groundwater-fed stream was associated with increased longwave, latent and sensible heat losses in winter because of larger temperature and vapour pressure gradients between the water column and the air. Furthermore, exchange of water with the hyporheic environment (Stanford and Ward, 1988; Poole and Berman, 2001) has been identified recently as having a significant effect on stream heat budgets. Story *et al*. (2003) estimated that hyporheic flows associated with channel steps caused significant daytime cooling, which had a magnitude of approximately 25% of the heat associated with the net radiation, while hyporheic exchange was a very significant component of the heat budget in the Von Guerard Stream, Antarctica (Cozzetto *et al*., 2006). Recent studies have emphasized the complexity of heat exchange at the stream bed and banks because gains or losses of hyporheic and phreatic water, often associated with features of channel geomorphology, such as pools and riffles and rock steps, are not only responsible for the advective transfer of heat but also affect gradients in bed temperatures that determine the nature of conductive heat exchange (e.g. Silliman and Booth, 1993; Evans and Petts, 1997; Evans *et al*., 1998; Poole and Berman, 2001; Curry *et al*., 2002; Alexander and Caissie, 2003; Story *et al*., 2003; Moore *et al*., 2005b; Cozzetto *et al*., 2006).

Field studies to document temporal variations in the nature of the river heat budget have also been conducted recently. Webb and Zhang (2004) monitored continuously the main non-advective heat fluxes affecting four streams of South–West England over a period of 1 year and demonstrated not only seasonal changes in the absolute but also the relative importance of individual heat inputs and outputs (Figure 1). Significant sub-seasonal variations in the components of the heat budget have been documented for the Girnock Burn in the Scottish Cairngorms, where complexities in the relationship between water temperature and net heat energy available to the stream, especially in periods of icing, were also evident (Hannah *et al*., 2004). Diel variability in heat fluxes associated with bed conduction and hyporheic exchange has also been the subject of recent investigation (e.g. Sinokrot and Stefan, 1994; Webb and Zhang, 1999; Johnson, 2004; Cozzetto *et al*., 2006).

In the absence of detailed information on heat fluxes, water temperature has traditionally been related to air temperature as a surrogate for net heat exchange and as an approximation to equilibrium temperature (e.g. Smith, 1981), but the nature of this relationship has come under closer scrutiny more recently (e.g. Johnson, 2003). The strength and sensitivity of the water–air temperature relationship has been shown to become greater as the length of the data-averaging period increases from sub-daily to monthly (Stefan and Preud'homme, 1993; Caissie *et al*., 2004) but this trend does not continue for annual means (e.g. Webb and Nobilis, 1997; Pilgrim *et al*., 1998), and streams affected by human modifications such as impoundments and wastewater inputs or by groundwater inflows generally have weaker air–water temperature correlations or lower regression line slopes (Erickson and Stefan, 2000; O'Driscoll and DeWalle, 2006). In addition, the water–air temperature relationship has been shown to depart from linearity not only at low air temperatures, as has been long appreciated (e.g. Crisp and Howson, 1982), but also at high air temperatures when the near-exponential increase of near-water-surface vapour pressure enhances evaporation and evaporative heat loss which imposes an upper bound change on stream and river temperatures (Benner and Beschta, 2000; Mohseni *et al*., 2002). In order to take account of these departures from linearity, Mohseni *et al.* (1998) proposed that the basic relationship between weekly water and air temperatures is best described by a logistic function. Mohseni and Stefan (1999) have also provided a physical interpretation of this nonlinear relationship based on the nature of upstream (groundwater, snowmelt and dew point) and equilibrium temperatures over four ranges of air temperature. Bogan *et al.* (2003) have investigated further the relationship between stream temperature and equilibrium temperature, which is defined as the water temperature at which the sum of all heat fluxes through the water surface is 0. At a weekly time scale, data for 596 sites in the eastern and central USA showed that mean stream temperature was linearly related to mean equilibrium temperature above 0 °C. Analysis of slopes and intercepts of the relationship suggested that only just over 20% of water courses studied had temperatures dominated by atmospheric forcing, while the remaining were influenced to some degree by cold-water inputs from groundwater, meltwater and deep reservoir releases, or by warm-water inputs from wastewater, cooling water and lake surface water (Bogan *et al*., 2003).

Increasing thermal capacity and travel time at higher flows has long been known to make streams and rivers less sensitive to atmospheric influences (e.g. Smith and Lavis, 1975). More recent studies have documented an increasing lag between water and air temperatures with increasing mean annual discharge (Stefan and Preud'homme, 1993) and changes in the slope of the water–air temperature relationship at different hydrological scales or over different flow ranges (Ozaki *et al*., 2003; Webb *et al*., 2003). The source, as well as the volume of runoff, has also been shown to affect water temperature behaviour (e.g. Kobayashi *et al*., 1999; Langan *et al*., 2001; Brown and Hannah, 2007), and rivers affected by seasonal snow- and ice-melt runoff commonly exhibit hysteresis in the water–air temperature relationship (Webb and Nobilis, 1994; Mohseni *et al*., 1998, 1999).

## THERMAL HETEROGENEITY AT DIFFERENT SCALES

One feature of recent studies has been the greater attention paid to the effects of spatial scale on the thermal behaviour and heterogeneity of water courses. Interest has increased in 'microthermal' gradients which comprise significant lateral and vertical temperature variations in the water column and its substratum over distances of a few centimetres to metres. Microthermal variability in water column temperature tends to be most pronounced in summer months under conditions of strong solar heating and low discharge volumes. For example, Clark *et al.* (1999) detected lateral or vertical temperature contrasts of at least 0·2–0·4 °C in 78% of 202 channel cross-sections surveyed in the River Frome and Bere Stream of southern England. Microthermal variation has been related to hydraulic factors such as the occurrence of dead zones along the margins of rivers, where shallower and slower flowing water is able to heat up more readily than that in the channel thalweg. Differences of upto 7 °C have been recorded between the shallows close to the bank and the main flow in small streams (Clark *et al*., 1999), while temperature elevation by more than 2 °C in dead zones of bends have been observed in the sizeable River Severn near Shrewsbury, central England (Carling *et al*., 1994). In contrast, Rutherford *et al.* (1993) reported only very small transverse variations, in the order of 0·03–0·05 °C, for the lower Waikato River, New Zealand. Previous interest in thermally stratified pools (e.g. Bilby, 1984; Ozaki, 1988) has continued in more recent years (e.g. Bormans and Webster, 1998) and especially in the context of ecological refugia (e.g. Nielsen *et al*., 1994; Ebersole *et al*., 2003). Different diurnal temperature behaviour has been recorded at depths greater than 4·5 m in pools of the North Fork of the American River, California, USA (Matthews *et al*., 1994), vertical temperature gradients have been observed to be more strongly developed during drought years in pools of streams in the English Lake District (Elliott, 2000), and strong thermal stratification, involving temperature differences of 15 °C between surface and deeper layers, has been monitored as seasonally persistent in deep (>10 m), naturally- or artificially-scoured pools of the Nepean River, New South Wales, Australia (Turner and Erskine, 1997a,b). Deeper sections associated with beaver dams were not found to cause strong thermal modification of headwater streams in Wisconsin, USA (McRae and Edwards, 1994). Shading by banks and riparian vegetation has also been shown to cause significant variability of temperatures in stream cross-sections depending on bank height, extent of cover and channel orientation (Webb *et al.*, 1996), while water in and above floating or rooted masses of vegetation in the stream channel may be more sensitive to solar radiation and develop higher temperatures than in the main body of the flow (Rutherford *et al.*, 1993; Clark *et al.*, 1999). It is now being recognized increasingly that thermal heterogeneity in the water column of small streams may be complex and controlled by the simultaneous influence of several factors including shading, groundwater inflows, hyporheic exchange and bed conduction (Story *et al.*, 2003; Malcolm *et al.*, 2004b; Danehy *et al.*, 2005; Moore *et al.*, 2005b).

Interest in the nature of temperature gradients and behaviour within the saturated interstitial spaces of bed and bank sediments of the hyporheic environment has grown strongly in recent years (e.g. Crisp, 1990b; Brunke and Gonser, 1997; Constantz, 1998; Webb and Clark, 1998; Caissie and Gilberson, 2003; Brown *et al.*, 2005; Hanrahan, 2007), and it is being increasingly realized that bed temperature gradients and hyporheic temperature behaviour are complexly influenced by many interacting factors, including water column temperature fluctuations (Acornley, 1999; Brown *et al.*, 2005, 2006a), climatic setting (Irons *et al.*, 1989; Valett *et al.*, 1990; Cozzetto *et al.*, 2006), the nature of bed sediments (Evans *et al.*, 1995; Malcolm *et al.*, 2002) and exchanges between surface and sub-surface waters which, in turn, are mediated by bedforms and other channel and riparian features (Evans and Petts, 1997; Malard *et al.*, 2001, 2002; Story *et al.*, 2003). Analysis of temperature-time series for the hyporheos has also proved an effective means of characterizing the spatial and temporal variability of groundwater–stream interactions (Constantz *et al.*, 1994; Silliman *et al.*, 1995; Malcolm *et al.*, 2004a; Hatch *et al.*, 2006; Schmidt *et al.*, 2006; Keery *et al.*, 2007), including the extent of percolation in ephemeral arid zone channels (Constantz and Thomas, 1996, 1997; Ronan *et al.*, 1998; Constantz *et al.*, 2001, 2002, 2003).

Considerable local thermal heterogeneity in water bodies has been documented recently across the riparian corridor of some floodplains, such as that of the River Danube, where lateral variation in temperature may be as great as 16 °C in summer (Ward *et al.*, 2001). The status of the connectivity between the main and distributary channels of the floodplain has been shown to strongly influence such thermal contrasts (Uehlinger *et al.*, 2003), which tend to diminish very significantly when flood pulses cause significant exchange of water between the main river and the riparian corridor (Tockner *et al.*, 2000). Although contrasts in water temperature along rivers has been emphasized (e.g. Rivers-Moore and Jewitt, 2004), in some systems, such as the Fiume Tagliamento in northeastern Italy, lateral contrasts in temperature across the braided floodplain, especially in downstream sections, are significantly greater than longitudinal differences in temperature between upstream and downstream reaches, which is thought to reflect a greater diversity of water-body types (Arscott *et al.*, 2001).

Recent studies of glacierized basins, which have attracted attention because of their particular sensitivity to climatic variability and change, have revealed considerable complexity and heterogeneity of thermal behaviour in alpine streams (Ward, 1994; Brown *et al.*, 2006a,b; Cadbury *et al.*, 2008); an example of which is presented in Figure 2. This may be related to runoff contributions from a range of sources with different thermal characteristics including meltwater from glaciers and snowpacks, karstic groundwater and hillslope aquifers (Brown *et al.*, 2005), the occurrence of freezing and contrasts in streamflow permanency (Brown *et al.*, 2006b) and downstream warming from cold-water sources (Uehlinger *et al.*, 2003), which is mediated by factors such as incoming tributaries, valley confinement and lakes in the proglacial environment (Milner and Petts, 1994).

While studies of the factors causing catchment, regional and countrywide variations in water temperature behaviour are well established (e.g. Collings, 1973; Mosley, 1982; Webb and Walling, 1986), there has been a renewed interest recently in statistical analysis to tease out the relationships between water temperature metrics and potential controlling factors operating over sizeable areas (e.g. Wehrly *et al.*, 1998; Lewis *et al.*, 2000; Scholz, 2001; Nelitz *et al.*, 2007). A wide range of predictor variables has been used in regression equations, although these often provide indices of catchment scale, macroclimatic context or reach-scale shading by riparian vegetation (Moore, 2005). Other factors, including local channel geomorphology and land-use effects (Hawkins *et al.*, 1997; Isaak and Hubert, 2001; Sponseller *et al.*, 2001; Scott *et al.*, 2002), have been included in analyses, but it has been rare for some potentially important controls, such as the presence of lakes and other lentic water bodies (Mellina *et al.*, 2002; Ham *et al.*, 2006; Pedersen and Sand-Jensen, 2007), glacier and snowfield cover (Cadbury *et al.*, 2008) and river regulation (Hamblin and McAdam, 2003) to be incorporated into regional predictions. However, Moore (2006) showed for catchments with drainage areas greater than 100 km$^2$ in British Columbia, Canada that stream temperature in all months increased with the extent of freshwater cover, while during the summer period, regulated water courses tended to be warmer than those with natural flows but temperatures became lower as the cover of snow and ice in a catchment increased. In this study of British Columbia, spatial patterns in monthly median temperatures were accounted for successfully by a relatively small set of catchment and climatic indices (Moore, 2005, 2006). However, more generally, the scale at which potential controls have an influence on variation in stream and river temperatures through space (Poole and Berman, 2001), and temporal changes in controlling factors (Arscott *et al.*, 2001), present challenging issues to resolve (Johnson, 2003).

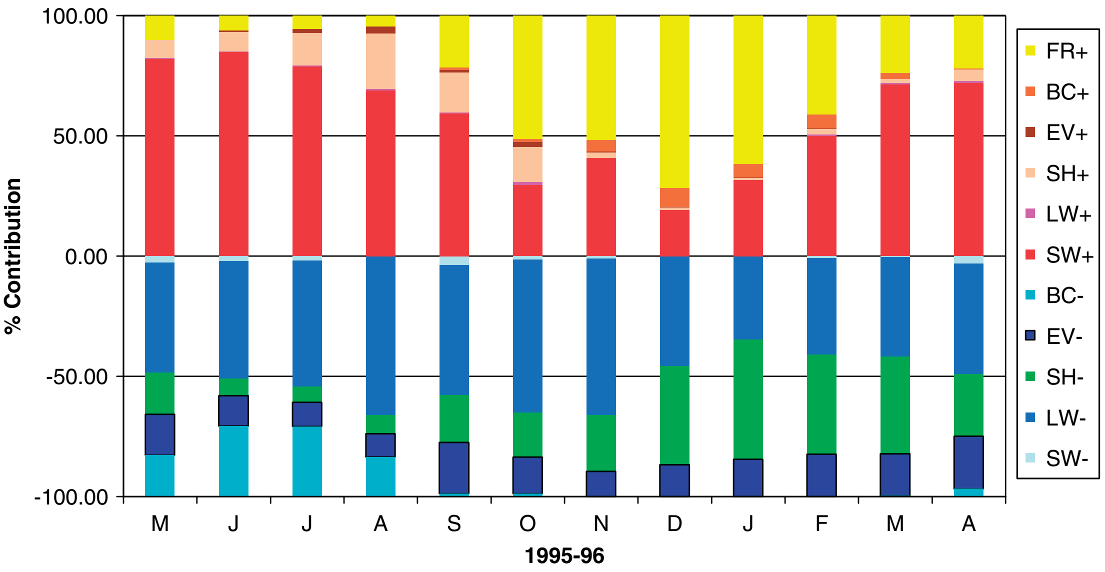

Figure 1. Annual cycle of mean monthly relative contributions of non-advective heat fluxes to energy gains and losses in the Black Ball Stream, Exmoor, South–West England. SW = shortwave radiation; LW = longwave radiation; SH = sensible heat; EV = evaporation/condensation; BC = bed conduction; FR = friction

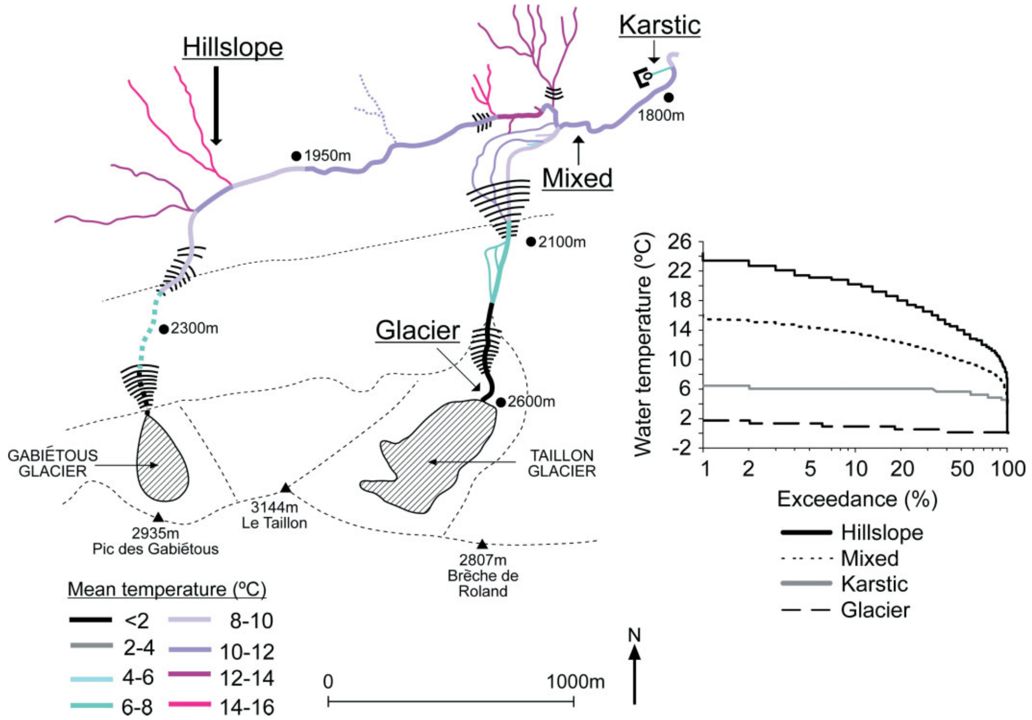

Figure 2. Basin-scale thermal heterogeneity during summer 2003 in the Taillon-Gabiétous alpine river system, French Pyrénées. Temperature duration curves [inset] summarize temporal stream temperature variability for four selected sites (steeper curves indicate more variable temperatures). Modified from Brown & Hannah (this issue)

## HUMAN IMPACTS

Studies of how human activity may alter stream and river temperature behaviour have continued to command attention in recent years. Poole and Berman (2001) noted that human impacts are effected through changing the amount or timing of the heat load delivered to the water course, or by modifying the flow regime, but also that streams differ in their sensitivity to human modifications and their assimilative capacity for heat. Forested catchments have distinctive thermal regimes (Weatherley and Ormerod, 1990; Malcolm *et al.*, 2004b; Webb and Crisp, 2006) that are readily disturbed by natural events, such as major storms and wildfires (e.g. Beschta and Taylor, 1988; Hitt, 2003) but especially by forestry practices (Beschta *et al.*, 1987; Binkley and Brown, 1993). Moore *et al.* (2005a) have comprehensively reviewed progress made in understanding stream temperature response to forest harvesting and have noted that debate still continues about the thermal impacts of forestry (Larson and Larson, 1996, 1997; Beschta, 1997). However, modern investigations in

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North America and elsewhere (e.g. Hostetler, 1991; Rowe and Taylor, 1994; Crisp, 1997; Johnson and Jones, 2000; Stott and Marks, 2000; Macdonald *et al.*, 2003a) have confirmed the findings from earlier studies (e.g. Swift and Messer, 1971; Graynoth, 1979; Feller, 1981; Lynch *et al.*, 1984; Holtby, 1988) that harvesting without leaving riparian buffers in temperate rain-dominated catchments significantly increases the summer-water temperatures and especially maximum values and diurnal range (Moore *et al.*, 2005a). An exception to this response was recorded by Jackson *et al.* (2001) for streams within clear-cuts in the Washington Coast Range, where shade provided by large volumes of slash and a substantially cooler post-harvest summer led to either a decrease or no change in daily maximum temperatures. Fewer investigations of forestry impacts have been conducted in snowmelt-dominated catchments, but similar, if somewhat more muted, increases in summer stream temperatures have been inferred from recent studies (Winkler *et al.*, 2003; Moore *et al.*, 2005a). Although riparian buffer strips have been used to reduce the effects of tree felling on summer-water temperatures (Moore *et al.*, 2005a), their effectiveness has been contested in recent investigations, and clear relationships between the extent of buffer strips and the degree of protection afforded have been demonstrated in only some studies (e.g. Davies and Nelson, 1994; Larson and Larson, 1996; Bourque and Pomeroy, 2001; Wilkerson *et al.*, 2006). The effects of windthrow have been shown to complicate the impact of retention riparian prescriptions (Macdonald *et al.*, 2003b), while a recent study of clear-cut harvesting, with and without riparian buffers in headwater streams of Briti significantly sh Columbia, Canada (Gomi *et al.*, 2006), suggests that the effectiveness of buffers is influenced by stream orientation. Further complexity in understanding the influence of forest harvesting on stream temperatures has been recognized in studies that have identified the moderating effects of headwater lakes and groundwater inflows (Mellina *et al.*, 2002), the impact of drainage in forest stands (Prévost *et al.*, 1999) and the role of forest roads (Herunter *et al.*, 2003). Investigations have continued in recent years to examine the extent to which temperatures raised by forestry practices persist in the downstream direction and the processes involved (e.g Zwieniecki and Newton, 1999; Story *et al.*, 2003; Johnson, 2004; Moore *et al.*, 2005a; Wilkerson *et al.*, 2006). Observations in second-order streams of Western Australia and south-east Queensland during summer showed temperature changes of ±4 °C, over distances covered in 2–3 h travel time, immediately downstream from 40–70% step changes in riparian shade (Rutherford *et al.*, 2004), although rates of downstream cooling below forest clearings have been found to vary with weather and hydrological conditions and maximum stream temperatures (Storey and Cowley, 1997; Keith *et al.*, 1998). Water depth and flow velocity also influence the rate at which stream temperature will come into equilibrium with changed atmospheric conditions in the downstream direction (Moore *et al.*, 2005a), but a modelling study of a hypothetical stream suggested temperature increases due to clearcutting could persist at least 10 km downstream into forested reaches (Bartholow, 2000). However, Moore *et al.* (2005a) have argued that cumulative effects of stream warming below clear-cuts are restricted by runoff from areas of intact forest, by nonlinearly additive effects of energy exchanges throughout a stream network, and by the moderating role of lentic water bodies which 'reset' temperature levels. The effects of forest harvesting on stream temperatures have also been shown to vary between years with different hydrological conditions (Hetrick *et al.*, 1998), while variable rates of longer-term thermal recovery following felling have been reported and reflect factors such as biogeographical zone, harvesting practices and the extent of catchment disturbance by debris flows (Johnson and Jones, 2000; Macdonald *et al.*, 2003b; Moore *et al.*, 2005a).

The consequences of agricultural practices, and particularly livestock grazing, for thermal regime has also been the subject of recent studies, which have inferred significant elevation of stream temperature with disturbance of the riparian environment through vegetation removal and stream widening and shallowing (Li *et al.*, 1994; Quinn *et al.*, 1997; Belsky *et al.*, 1999; Isaak and Hubert, 2001), although the influence of land use has also been considered small compared to that of weather conditions (Borman and Larson, 2003). An example of progressive increases in water temperature, consequent on continuing damage to the riparian zone by the development of agricultural land and river channelization, is provided by the Toikanbetsu River of northern Japan, where it is estimated that summer maximum temperatures have increased from 22 °C in 1947 to 28 °C in 1989 (Nagasaka and Nakamura, 1999). Destruction of riparian vegetation is one of the anthropogenic stressors identified as changing water temperature behaviour in catchments that have undergone urbanization (Krause *et al.*, 2004; Nelson and Palmer, 2007), and which may lead to the degradation of cold-water stream habitat (Wang and Kanehl, 2003). However, a recent study of streams in central Tokyo and its suburbs (Kinouchi *et al.*, 2007) has shown that inputs of heat from wastewater can also be a major cause of increases in the water temperature of urban environments. Recent investigations have emphasized the occurrence of thermal heterogeneity in urban streams and identified warming by 1–10 °C of water retained in construction site sedimentation basins in Pennsylvania, USA (Ehrhart *et al.*, 2002) and the occurrence of temperature surges of more than 7 °C linked to localized rainstorms at urbanized sites in small watersheds of the Piedmont region of Maryland, USA (Nelson and Palmer, 2007), which may reflect runoff washing over hot pavement surfaces (Galli and Dubose, 1990).

An interest in the effects on river temperatures of changing river flow through diversion, abstraction and impoundment has also continued in recent years. The nonlinear impact of decreased flow depth and velocity on summer time temperature maxima and diurnal range has been modelled for the Platte River, Nebraska, USA

(Gu, 1998; Gu *et al.*, 1998), while Tvede (1994) has demonstrated that diversion of cold snowmelt runoff into hydroelectric power (HEP) plants in the Aurland River basin, Norway has resulted in elevated summer temperatures below the point of abstraction. A study of a small stream in the southern Swiss Alps (Meier *et al.*, 2003) indicated that water diversion for HEP generation would have only a minor effect on the temperature of very steep river sections, where dissipation of kinetic heat energy is the dominant process, but would be more significant for reaches of lower slope. Stringham *et al.* (1998) have suggested that irrigation water returning to the river by sub-surface routes has the potential to moderate diurnal temperature range, echoing earlier findings from the Yakima River, Washington, USA (Sylvester, 1963).

One of the major human impacts on thermal regimes of rivers that has attracted attention over many years is the effect of regulation and impoundment (e.g. Nishizawa and Yambe, 1970; Lavis and Smith, 1972; Lehmkuhl, 1972; Ward, 1974; Crisp, 1977; Walker *et al.*, 1978; Stanford and Ward, 1983; Webb and Walling, 1988a,b; Byren and Davies, 1989; Palmer and O'Keeffe, 1989; Voeltz and Ward, 1989). Continuing investigations have stressed the complexity of thermal responses to impoundment as a result of processes occurring within reservoirs (Hamblin and McAdam, 2003) and downstream (Dolz *et al.*, 1994; Malatre and Gosse, 1995). Significant inter-annual variation in the impact of reservoirs on downstream temperatures has been recognized (Figure 3) and attributed to year-to-year changes in climate conditions, reservoir operation and behaviour, and tributary inflows (Webb and Walling, 1993a, 1996; Preece and Jones, 2002). With more detailed monitoring, varying short-term temperature responses to alterations in the volume and level of flow releases have been observed (Webb, 1995; Webb and Walling, 1997). A study in the former Czechoslovakia (Patera and Votruba, 1996) suggested that relative reservoir capacity, expressed as the time taken for a reservoir to fill, was a useful discriminator of the effects of an impoundment on river temperatures, while investigations of the downstream persistence of temperature modifications has highlighted complicated patterns of recovery in systems regulated by multiple dams of different types (O'Keeffe *et al.*, 1990). An interesting pattern of 'nodes' and 'antinodes' in the extent of diel variation may develop at different distances downstream below large dams reflecting the effect of travel time of water released from the reservoir (Lowney, 2000). Interest in the downstream impact of river regulation on thermal regime continues to be stimulated by ecological concerns (e.g. Liu and Yu, 1992), and modelling has been undertaken recently to investigate what changes in water temperature and, in turn, in fish survival would accrue in the spawning sections of the River Klamath, California, USA by removing a series of dams below Upper Klamath Lake (Bartholow *et al.*, 2004).

## PAST AND FUTURE TRENDS IN WATER TEMPERATURE

Attention in recent years has also been increasingly focussed on how stream and river temperatures have changed in the past and might do so again in the future, and the main factors responsible (Webb, 1996b). The accumulation of data from routine surveillance and monitoring (e.g. Webb and Nobilis, 1995; Hammond and Pryce, 2007) and in long-term research investigations (e.g. Webb and Walling, 1992, 1993b; Langan *et al.*, 2001) has facilitated recent analysis of past temperature trends. Most studies report increases in water temperature detected or estimated over decadal to centennial time scales (e.g. Bartholow, 2005; Moatar and Gailhard, 2006), although Smith (1995) recorded a median change of −0·28 °C per year in New Zealand rivers during the period 1987–1993, while maximum temperatures in the middle reach of the River Trent in England have declined significantly since the mid-1970s (Langford,

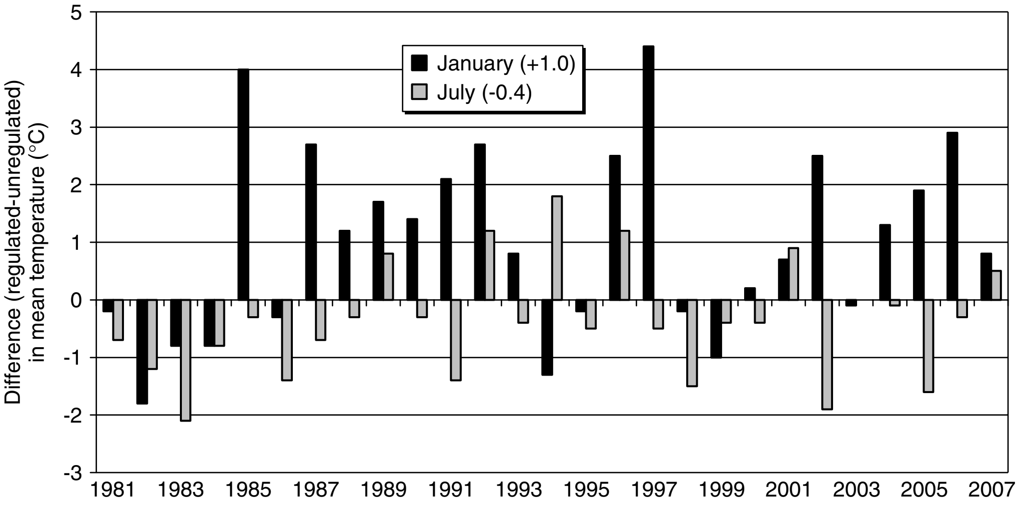

Figure 3. Long-term variation in the impact of Wimbleball Reservoir, Exmoor, South–West England expressed as the difference in January and July mean temperatures between the regulated river 0·3 km below the dam and a neighbouring unregulated control stream. Study period average differences in January and July given in inset

*pers. comm.*). The former decrease was ascribed partly to the eruption of Mount Pinatubo in the Philippines and partly to El Niño Southern Oscillation (ENSO) variations, while the latter reflects the decreasing influence of cooling water discharged from power stations because of closures and installation of secondary cooling systems.

Considerable variation in the magnitude of river temperature rises is apparent between and within river systems. For example, an analysis of records from 13 sites in the Klamath River of California with more than 10 years of data revealed a wide variation around the basin-wide average warming trend of 0·026 °C per year (Bartholow, 2005), while Hammond and Pryce (2007) reported that increases in river water temperature over the last 20–30 years have been particularly apparent in the Anglian, Thames and South-West regions of England. Annual mean temperatures appear to have risen over the course of the 20th century in Austrian rivers by typically *ca* 1 °C, but increases have been more marked in catchments with a large upstream lake area and at sites on the mainstream of the Danube affected by barrage construction for HEP generation, while little or no change has been recorded for stations in the headwaters close to glacier and snowmelt sources of runoff (Webb and Nobilis, 1994, 1995). Furthermore, some variability has been demonstrated in the extent to which river temperatures in different seasons have been subject to rising trends. Langan *et al.* (2001) found that spring (March–May) temperatures had exhibited most changes in the period 1968–1997 and had risen by 2 °C. Figure 4 displays trends in July and January mean temperatures for a small upland catchment of South–West England and shows little evidence of an increase in midsummer values but indicates a significant rise in those of midwinter.

Although some rises in water temperatures, such as the increase of 0·11–0·21 °C year$^{-1}$ recorded in winter and spring for some stream segments in central Tokyo and its suburbs between 1978 and 1998, can be ascribed to increases in anthropogenic heat input from urban wastewater (Kinouchi *et al.*, 2007), changes in stream and river temperatures during recent decades have often been attributed to climatic drivers. In the case of western Europe, there is evidence that the climate pattern of the North Atlantic Oscillation (NAO), which governs the strength of the westerly winds and influences the amount of heat advected from the Atlantic Ocean, is strongly related to fluctuations in midwinter stream temperatures (e.g. Elliott *et al.*, 2000). The influence of NAO on river temperatures has been shown to penetrate to central Europe (Webb and Nobilis, 2007), while Hari *et al.* (2006) have demonstrated, from analysis of very high resolution records collected in 25 alpine streams

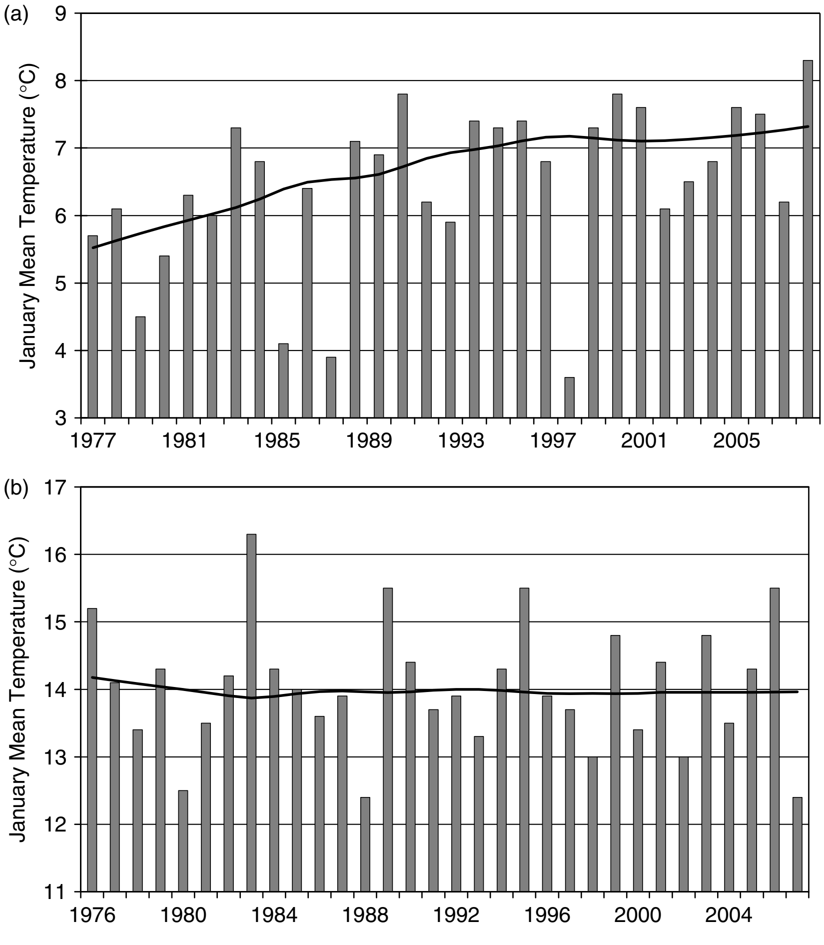

Figure 4. Long-term trend in January (A) and July (B) mean temperatures in the River Pulham, Exmoor South–West England defined by LOWESS curves

and rivers of Switzerland, that substantial warming has occurred during the last quarter of the 20th century and have suggested that an abrupt increase in 1987–1988 is correlated with a shift in NAO to a highly positive phase at that time. In other areas, trends in water temperature may be influenced by more than one climate pattern, which operate over different timescales. In the East Creek of British Columbia, Canada, Kiffney *et al.* (2002) showed mean winter (January–March) water temperatures reflected the influence of ENSO and the Pacific Decadal Oscillation, and tended to be highest when the latter was in phase with El Niño years. Trends in temperature over recent decades are not only related to major climate patterns; Durance and Ormerod (2007) have shown that forest and moorland streams in the uplands of central Wales have warmed by 1·4 and 1·7 °C, respectively between 1981 and 2005, after accounting for NAO effects. Furthermore, in many river systems, the effects of increasing human impact are superimposed on the influence which climate patterns and climate change may have on water temperature trends over the 20th century. For the Columbia and Snake rivers of the USA, Petersen and Kitchell (2001) have shown how average July temperatures since 1930 have not only responded to climate shifts but also to progressive impoundment of these major river systems, while the effects of reservoir regulation in increasing early, but decreasing mid, open water season temperatures of tributaries in the Lena River in Siberia over the period 1950–1992 has also been documented (Liu *et al.*, 2005; Yang *et al.*, 2005). It is being recognized increasingly that water temperature trends in major rivers over the past century are a complex function of the interaction of climate and hydrological changes, major climate patterns and increasing human impacts which include not only impoundment and barrage construction but also urbanization and heated effluent discharges (Moatar and Gailhard, 2006; Webb and Nobilis, 2007).

The future trajectory of stream and river temperatures is beginning to command as much, if not more, attention than the nature and magnitude of past trends, and attempts to predict future thermal behaviour have been made by statistical and deterministic modelling approaches (e.g. Mackey and Berrie, 1991; Stefan and Sinokrot, 1993; Sinokrot *et al.*, 1995; Kyle and Brabets, 2001; Morrill *et al.*, 2005). Potential increases in water temperatures between 1 and 9 °C, as a consequence of global warming because of a projected doubling of atmospheric $CO_2$ levels by 2050, have been predicted for a range of water courses in the USA and UK (Webb, 1996b). However, caution is needed in making future estimates because the magnitude and nature of projected future temperatures may vary considerably depending on the Global Circulation Model used, as Cooter and Cooter (1990) demonstrated in a study of future July water equilibrium temperatures in the south-eastern United States. Furthermore, the extent of future rises in stream and river temperatures may be mediated by catchment characteristics, such as the extent of forest cover, the magnitude of groundwater inflows and facets of catchment topography, such as stream orientation. The spatial patterns in river temperature rises may, therefore, differ from those of the changes in driving climate variables (Webb and Walsh, 2004).

Stream and river temperatures in different parts of the year may not be affected to the same extent by future climate change (Webb and Nobilis, 1994; Pedersen and Sand-Jensen, 2007). In one of the most comprehensive studies undertaken, Mohseni *et al.* (1999) demonstrated from projections at 764 stations across the USA, that most streams will have maximum temperature increases by 2050 in spring, but in January for several sites in cold regions and in autumn for a smaller number of stations. In contrast, the minimum rises in temperature were projected generally for the months of December, January, July and August. Furthermore, this study indicated that rises at the scale of the continental USA were likely to be greater for mean annual values (2–5 °C), rather than weekly extremes (1–3 °C), reflecting the sigmoidal relationship between water and air temperatures (Mohseni *et al.*, 1999).

In assessing how stream and river temperature may change in the future, account also needs to be taken of the less direct impacts of changing climate. These include alteration of riparian vegetation (Cooter and Cooter, 1990) which, in turn, may alter radiative heat exchanges in the channel, and also the occurrence of different hydrological conditions. Meisner (1990) demonstrated that it was important to include changes in groundwater, as well as air, temperature in a study of future downstream temperature profiles in the Rogue River, Southern Ontario, Canada, while Morrison *et al.* (2002) highlighted the effects of changing flows in the Fraser River, British Columbia, Canada. Computer modelling suggested that by the period 2070–2099, an increase in the spatial and temporal frequency of temperatures exceeding 20 °C would occur, particularly below the confluence with Thompson River, as a consequence of changes in the magnitude and timing of the spring snowmelt freshet.

## CONCLUSIONS

While Blakey (1966) was able to suggest 'temperature is probably the most important, but least discussed, parameter in determining water quality', the last 15–20 years has seen an upsurge of interest in the thermal behaviour of stream and river systems. Recent advances in monitoring and in modelling have facilitated greatly the collection and analysis of information, and an increasing number of field investigations have revealed the complexity of the heat fluxes fundamentally controlling water temperature behaviour. In particular, the importance and complexities of energy fluxes associated with exchanges of water between the channel, hyporheos and phreatic zones have been highlighted by recent research. A greater understanding of the physics of heat in rivers is also informing the development and application of relationships between water temperature and hydrometeorological variables, such as air temperature. Gaining an understanding of thermal heterogeneity in watercourses over a range of scales provides an ongoing challenge, while, despite long-standing interest, the manifold ways by which human activity may modify thermal regime continue to stimulate research. The potential effects of anthropogenically induced climate change have provided a recent significant impetus for investigation of stream and river temperatures, although a growing number of investigations of long-term trends highlight the complexity of climate drivers of change and the interaction with other human impacts.

Temperature studies continue to attract attention from a wide range of disciplines including hydrology, engineering, forestry science, ecology, climatology, mathematics and geography. Furthermore, the findings of recent research are informing those who have the responsibility of managing rivers and setting water quality criteria related to temperature (e.g. Essig, 1998, 2003; Ice *et al*., 2004). Recent investigations have revealed many hitherto unappreciated subtleties in the nature of the thermal behaviour of lotic systems. However, there is scope to further advance our knowledge of the themes discussed in this review, and given the importance of temperature to freshwater ecology and the sensitivity of this water quality parameter to environmental pressures, it can be anticipated that studies of thermal behaviour of stream and river systems will remain a growing research area in the future.

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