WIREs Water

What else do managers need to know about warming rivers? A UK perspective

Journal:	*WIREs Water*
Manuscript ID:	WATER-065.R1
Wiley - Manuscript type:	Opinion
Date Submitted by the Author:	n/a
Complete List of Authors:	Orr, Harriet; Environment Agency, Evidence Johnson, Matthew; Nottingham University, Geography Wilby, Robert Hatton-Ellis, Tristan; Natural Resources Wales, Broadmeadow, Samantha; Forest Research,
Choose 1-3 topics to categorize your article:	Water and Environmental Change (2WEC) < Science of Water (1SCW), Water Quality (2WQL) < Science of Water (1SCW), Conservation, Management and Awareness (2CON) < Water and Life (1WLF)

What else do managers need to know about warming rivers? A UK perspective

First author	
*Harriet G Orr, Environment Agency, UK. Harriet.orr@environment-agency.gov.uk	
Second author	
Matthew F Johnson, Department of Geography, University of Nottingham, UK	
Third author	
Robert L Wilby, Department of Geography, Loughborough University, UK	
Fourth author	
Tristan Hatton-Ellis, Natural Resources Wales, UK	
Fifth author	
Samantha Broadmeadow, Forest Research, UK	

Abstract

River flow and water temperature are fundamental controls of freshwater ecosystems. Hence, future warming could impact valued habitats and species, particularly those with cold water preferences (such as salmonids). Warming could also exacerbate existing environmental pressures or diminish the effectiveness of management interventions. Climate model projections provide compelling evidence of the need for adaptation despite uncertainty about the timing, nature and distribution of impacts on water quality, vulnerable species and habitats. Low regret adaptation options to manage temperature impacts include increasing riparian shade, enhancing thermal refugia and removing thermal barriers or hotspots. Indirect controls include managing river flows through abstraction and discharge regulation, moderating flow control structures and the manipulation of channel hydromorphology. However, fundamental gaps in understanding may limit the effectiveness of some of these measures, leading to undesired side-effects, wasted resources, ineffectual outcomes or limited uptake. These knowledge gaps include where to target measures, how to implement in different situations, how to maximise co-benefits and integrate with other policy objectives and how to support implementation across rural and agricultural landscapes. Despite many uncertainties, restoration of riparian shade and river flows has the potential to deliver multiple benefits even if this does not include retarding rates of warming.

1. Introduction

Mean annual Central England air temperatures have warmed by 1°C since 1980[1] and river water temperatures warmed by an average of 0.03°C per year between 1990 and 2006[2]. There is high confidence that climate change will result in further increases in air temperatures across the UK, particularly in summer[1]. River water temperature is also expected to rise although rivers will be differentially sensitive to warming[3]. Concurrent hydrological and land-use changes could also magnify or reduce changes in water temperature[4] with reductions in low flows contributing to this warming[5].

Warming presents challenges to river custodians. For example, fishery managers are concerned about the impact of warming on cold water species, increases in the abundance of warm water species, and the spread of disease and invasive organisms[6,7]. Ecological responses to climate change are being detected[8] but confidence in projected change in rivers is low[9], especially in comparison to lakes for which a range of impact assessment tools exist[10]. Uncertainty comes from difficulty detecting and attributing change in ecosystems where impacts may be direct (e.g. phenological changes), indirect (e.g. changing community composition and species interactions), immediate or progressive[11]. Impacts may also be masked by other changes such as improvements in water quality[12]. Higher temperatures could also lead to deterioration in river water quality, but few studies explore how soon such impacts may be realised[5,13,14]. Coincident monitoring of ecological and hydrological parameters can help to overcome some of these difficulties in detection of change but in the absence of certainty of impact an alternative approach is to focus on ways to manage water temperature to minimise potential detrimental impacts.

High summer temperatures are a “critical characteristic of habitat quality” for salmonids because temperature affects metabolic rates and dissolved oxygen in water declines with increasing temperature, potentially increasing stress and susceptibility to disease for cool and cold water fish[15]. However, there are large uncertainties about how changing water temperature will impact on freshwater ecosystems. For example, will nocturnal animals be more sensitive to changes in night-time temperatures rather than widely studied maximum temperatures recorded during day-time[16]? It is clear, however, that warming water as a result of climate change is a risk to ecological objectives, including the achievement of “Favourable Conservation Status” for Atlantic salmon in Britain under the EU Habitats Directive[17]. Warmer temperatures are also expected to influence riverine metrics used to assess compliance with the EU Water Framework Directive (WFD), either because they are directly sensitive to temperature change (e.g. algal cover, presence of temperature-sensitive fish) or because the ecological effects of temperature are inter-related with other pressures, such as nutrient availability, that available assessment tools are designed to measure (e.g. Trophic Diatom Index, River Macrophytes Nutrient Index, Number of Invertebrates Taxa and Average Score per Taxon). It does not necessarily follow that the resulting classifications are ineffective since the ecosystem is being harmed by an external combination of pressures but, incorrect diagnosis of the pressures may lead to ineffective programmes of measures.

River water temperature is determined by complex energy exchanges. In the UK on average, 70 % of these are from radiative fluxes; other fluxes include those generated by friction between flowing water and the river channel, advected water from upstream and groundwater inflows[18]. The relative importance of different fluxes changes between seasons, through time and between locations and the sensitivity of river reaches to radiative fluxes is partly controlled by the surrounding topography and vegetation[18,19]. Human endeavours alter thermal regimes, for example, through land use changes, impoundments, discharges, abstractions and channel and river flow management[20,21,22,23].

Important controls from a management perspective are those that determine a river's sensitivity to warming (channel morphology and size, presence of riparian shade, influence of groundwater) and the potential for interventions to change thermal regimes. River thermal processes although complex are broadly understood but, it is hard to quantify the importance of different components of the thermal regime for individual river reaches[24].

Water quality and abstraction are regulated in many countries. For example, water quality and ecological thresholds are set in legislation across Europe (e.g. WFD) and although it is unclear whether existing measures will remain effective in the future, climate control measures do exist. In contrast, to date, relatively little regulation has been deemed necessary to address thermal discharges. (In the UK thermal discharge standards are generally only used for the release of power station cooling water). Warmer rivers, together with increased demand for water services, may make water quality targets harder to achieve. Consequently, new solutions may be needed, such as separating clean and dirty water runoff by removing combined sewer overflows, harvesting nutrients at water treatment works and relocating water treatment infrastructure. It would be helpful to better understand how much the direct management of rising water temperature might contribute to meeting water quality objectives by building resilience to future change.

Conservation agendas are focused on building resilience into ecosystems by reducing environmental pressures, improving habitat quality and creating 'more, bigger, better and more connected' habitats to enable natural adaptation[25]. Setting adaptation objectives is one thing, but the real work lies ahead in practical implementation[25]. Despite uncertainty, the risks posed by warming rivers have inspired 'low regrets' adaptation measures (sidebar 1). In addition, actions directed at improving habitat quality by addressing existing pressures may also provide future resilience to warming waters, such as restoring engineered channels and removing unsustainable abstraction[26]. Interventions may be a means of 'buying time' for ecosystems to adapt[27] but, more work is needed to formally test the efficacy of such measures against future change scenarios[9].

Tools are beginning to be developed that translate process understanding into guidance for decision makers[28] but their development and use in the UK is limited even where detailed catchment studies have provided suitable data[29,30]. We suggest that the wider development and use of tools could aid adaptation to future climate change but is hampered by a lack of readily available data and information about local catchment controls on water temperature and the exposure of rivers to avoidable warming. More specifically a lack of extrapolation from experimental studies in ways that are decision-relevant continues to impede progress. Management is also hampered by lack of certainty about the effectiveness of management interventions to control water temperature in a range of situations. This presents challenges for understanding the impact of rising temperature on ecological and bio-chemical processes and the ability to measure the success of adaptation strategies, such as riparian shading[31].

In this paper we: 1) discuss the data required to characterise thermal regimes, detect significant change in river water temperature and inform management decisions; 2) consider recent efforts to plan and implement adaptation strategies in the UK and 3) present future research priorities to support those involved in river (water temperature) management.

2. Measuring river thermal regimes and detecting change

2.1. Monitoring networks and methods

Concern about future warming has led to increased focus on detecting recent trends[2]. Such endeavours may eventually help identify river reaches that are particularly sensitive or vulnerable to future warming, provide a baseline from which to make projections about future change, and a basis for prioritising resources for interventions. However, a lack of long-term, high resolution water temperature data and the coarse spatial density of available measurements of water temperature and other energy balance components, have so far limited our capability for physical modelling in this area. Despite general indications of why some river reaches are more sensitive to warming[4].

What and how we monitor depends on what we wish to detect and at what scale. For example, remote sensing and towing sensors have wide spatial coverage but only provide a snapshot in time[32], whereas process-based methods and the construction of heat-budgets provide detail, but very limited spatial coverage. Fibre-optics can provide very high temporal and spatial resolution data, but currently only cover ~1 km[33]. Distributed networks of high-resolution temperature sensors provide good spatial and temporal resolution, but extrapolation is required when considering between-site thermal characteristics[34]. We could extend centralised monitoring (primarily for water quality compliance) with a range of techniques at a variety of spatial scales to address under represented urban, upland and headwater streams[2,36]. Upland networks with other focuses are beginning to accommodate water temperature to partly address this gap (UK Environmental Change Network and the Upland Waters Monitoring Network). However, centralised funding is required to maintaining long-term monitoring networks beyond only a very few sites.

Longer and higher-resolution time-series, typically maintained by research institutions, yield important process insights, but tend to be limited to few sites[19,30] or intensively studied catchments[16,29,37]. Knowledge gained in this way provides general principles for managers[38] and UK based studies lend confidence that effects observed elsewhere are also applicable here[21,23,39]. However, managing water temperature within individual reaches or catchments requires more work to characterise thermal regimes everywhere. Some options include:

- Extending regime information to generalise beyond discrete monitoring sites. This is likely to require data about catchment topography, vegetation and a need to identify what aspects of temperature are important to convey but could use stream network models[40].
- Map catchment thermal habitat quality, including refugia, from general principles that relate water temperature to the amount of riparian vegetation, geological and climatic region, hill shade, channel modification, etc.

- Develop physically-based water temperature models and calibrate for UK river types.

2.2. Data sharing and open access

The need for high density, high resolution temperature data over large spatial areas to inform guidance, optimise management programs and calibrate statistical and process-based models, means that data-sharing is essential. Examples do exist[28] however, open access is unusual and can be difficult even where there is a willingness to share. The increase in free web-hosting and the availability of large data storage and file-sharing facilities makes sharing data easier[35]. However, resources are required to establish and maintain large data repositories[27]. Establishing a community data sharing platform could support future research and maximise value from short or disparate temperature records and might also support greater application of technologies such as remote sensing of water temperature[41].

2.3. Standardised methodologies

Attributing climate change as the cause of changes in water temperature requires either a fuller understanding of local processes or the ability to observe impacts over large areas to be confident that other local influences are not driving change. However, political, economic and statutory drivers result in patchy data coverage with individual monitoring schemes often having different methodologies. Standardised protocols for recording water temperature can help ensure equivalence and quality of data, whether the data are centrally managed formal networks or extensive data gathering via citizen science[42,43].

2.4. Information needed to assist adaptation decisions

In the UK, warming has been most marked in winter[1,2] but, it is generally hot summer day increases that have inspired adaptive action. Ecological considerations of water temperature are often focussed on the upper, fatal threshold of a few species of economic importance, such as salmonids. However, sub-lethal temperatures directly impact the metabolism, growth and life-cycle (i.e. phenology), particularly of cold-blooded animals. For example, change in the timing of development and emergence of invertebrates has been related to rising river temperatures[44], invertebrate communities are influenced by riparian shade[45].

A wider consultation and review of evidence to determine thermal indicators with biological significance might help focus management attention. For example, is it daily maximum, minimum or mean temperatures, diurnal or seasonal temperature ranges, or indirect effects, such as dissolved oxygen dynamics, that are of most significance to organisms? Clearly, the answer is species and/or habitat specific, so the purpose of monitoring (whether for early detection of environmental change, routine reporting for water quality compliance, or elucidating the benefits of management) needs to be clearly articulated.

Enabling the wider use of knowledge generated from research requires a raft of considerations[46] but primarily requires provision of spatially representative information about thermal regimes and the state of the environment in terms of natural controls of water temperature.

3. Planning and implementation of adaptation strategies

3.1. Adaptation planning

Options to directly buffer undesirable impacts of warmer rivers include: creating or protecting refugia where organisms can avoid high temperatures, attempting to reduce warming by increasing shade, managing river flows, or tackling thermal hotspots such as shallow, degraded or exposed channels. The UK Government has a National Adaptation Plan to build resilience to climate change that includes actions to improve the natural environment[35]. However, it remains the case, in the UK as with other countries, that practical implementation of adaptation is less often about building the capacity of natural, institutional and social systems and more often based on engineering and technological solutions[47]. Riparian tree planting has been adopted as a practical intervention by the Environment Agency specifically to improve the capacity of rivers to sustain salmonids in the face of recent and future warming in a Keeping Rivers Cool (KRC) initiative (sidebar 1). Of course, riparian trees planting has been proposed for a range of other purposes including to improve habitats and reduce river bank erosion, and runoff of polluted waters[48,49,50,51]. Here we present KRC as a case study of the evidence provided and gaps in understanding that could limit uptake of riparian shading as an example adaptation measure. We also make links to other measures that could improve the adaptive capacity of river ecosystems.

3.2. Supporting evidence for riparian tree controls on water temperature change

Much of the evidence of woodland impacts on stream temperature originates from studying the impacts of forest removal on, particularly maximum, temperatures in the United States[22]. [Although not the focus of the present Opinion article, the literature on forest harvesting may help anticipate some of the thermal consequences of widespread Ash die back in the UK]. A systematic review of the effects of trees on water temperature found maximum temperatures were, on average, 3 °C lower in wooded areas, but the range of values was large[38]. Variations in shading effects may be due to differences in the width and length of woodland buffers, the influence of groundwater as well as stream width to depth ratios. A greater understanding of this variation could help target riparian planting initiatives where they would be most effective.

The greatest impacts from riparian shading are likely to be experienced in smaller streams because downstream reaches will be buffered by the thermal inertia of greater water volumes (see review)[20](Fig. 1). Conversely, lower reaches of rivers are less likely to benefit from shading, not least because of the impossibility of achieving canopy closure above the water surface and because of the dominance of heat advection from upstream. The threshold where shading becomes less effective is unknown and likely to be dictated by catchment characteristics (such as landscape shading), dominant hydrological pathways (such as presence of wetlands, springs or tributaries), climatic regime (such as dominance of snowmelt, indirect effects on vegetation cover, occurrence of extreme temperatures or storms) and artificial influences (such as water released from reservoirs).

Recent field studies indicate that beneficial cooling can be achieved with 100 - 500 m long buffer strips with 20% canopy cover [23,52]. For example, an Australian study suggests that the effects of patchy shade on temperature appear to last up to 1 km downstream (2nd order streams, width 1–2 m, depth 5–15 cm, velocity 5–10 cm s^{-1})[31]. A study of shaded and unshaded sites along a latitudinal gradient in Europe, recorded 2.5 °C lower average temperatures associated with shaded sites of 500m length along the river bank, and a maximum cooling effect of 12.5 °C during hot weather[52]. The same study[52] notes that ecological benefits need longer shaded sections of 1 km and speculate that this should be a mosaic of shaded and unshaded sections. A better understanding of the size of woodland blocks and distance between them along the stream length would help managers target planting. We can account for factors such as the extent of existing shade and aspect but others, such as groundwater influences, are unlikely to be fully known. This could limit the effectiveness of planting in some locations, lead to undesired side-effects, wasted resources or limited uptake. Riparian tree planting is generally regarded as a 'low regrets' option, with multiple additional benefits, which may still be realised even where temperature regulation is not[53].

3.3. Information and tools to support tree planting and address knowledge gaps

Evidence gathering for KRC focused on making the case for support, providing information and developing tools to help planning and planting. This included meta-analyses of how trees impact river water temperature[38], mapping existing riparian cover (Fig. 2), production of shade maps to target planting and guidance on planting schemes. The shade generated by riparian trees varies depending on aspect, situation and local topography and conifer forest can have very different impacts on stream ecosystems than broadleaved trees. Shade maps have been produced based on summer solar radiation (insolation) for stretches of river channel for all catchments in England. Shade on individual reaches is relative to neighbouring reaches within a catchment and incorporates the effects of landscape and tree shading. The maps are available to a range of organisations through the Rivers Trusts website[54] and help those working with landowners discuss why some locations may be preferable for planting. A guidance document includes evidence about temperature impacts, planting designs, constraints, maintenance programmes, case studies and links to resources, expertise and funding streams.

Based on a digital river network[55] we identified 68% (total stream length 271,911 km) of streams in England and Wales as 1st or 2nd order, highlighting the significant under-representation of headwaters in monitoring strategies (Table 1). Using Aerial Light Detection and Ranging (LiDaR) imagery, which provides accurate topographic information about the land (and vegetation surface), we estimate that 15% of channels in England and Wales have riparian trees, defined as vegetation objects greater than 2.5 m high (Fig. 2). This figure is an estimate because, although the data are highly accurate, LiDaR is not available for some areas: hence the gaps shown in white and some of the coloured water bodies may have up to 50% missing data in (Fig. 2). LiDaR and remote sensed imagery may provide useful over-arching information about large areas of river, supporting higher temporal resolution measurements made from distributed networks in target catchments. Further resolution may be necessary where critical thermal refuge or detrimental 'hot-spots' exist, which could be monitored with fibre-optic cables. A targeted, nested hierarchy of monitoring techniques could provide the information to map and quantify thermal characteristics for a range of UK river types.

4. Future research needs

A workshop held in September 2013, supported by KRC, facilitated knowledge exchange between researchers, river custodians and managers, and special-interest user-groups, with a focus on climate change adaptation in freshwaters. Pre-workshop questionnaires, sent to sector representatives, yielded consensus on knowledge gaps which shaped workshop themes. Discussions identified actions to provide: a better understanding of thermal refugia, more information about how measures other than riparian shade contribute to managing water temperature and thermal impacts on instream ecosystems.

Some of the questions emerging from workshop discussions are listed in Table 2 and further elaborated by the authors. In support of wider uptake and increased impact from riparian shading initiatives the most pressing lines of enquiry are around the arrangement of trees and the size and spacing of buffer strips. For longer term planning we need to identify the critical locations in catchments where riparian shade will be most effective perhaps by identifying existing refugia.

Quantifying other ways to influence water temperature for example by managing control and impoundment structures, abstraction and urban runoff would support more integrated management of water temperature and help achieve multiple objectives from water quality and flood protection activities.

Further investigating the indirect impacts of warmer rivers on river ecosystems, specifically the interactions between flow, temperature and dissolved oxygen would help evaluate the performance of options designed to maintain water quality standards. The development and application of catchment water temperature models could also help here.

Finally, we need new tools and ways of melding disparate information sources to get greater value form them to inform practical decisions about thermal management beyond experimental catchments. This will involve development of modelling techniques that are physically plausible yet robust to variations in data quantity and quality. There may be lessons to be learnt from recent 'Big Data' initiatives in other areas of global change research[56].

5. Conclusions

Options exist to manage some of the negative impacts of warming rivers. New understanding about water temperature regimes is emerging from research endeavours but, more work is needed to ensure we maximise the use of available information to support practical adaptive decision making.

We need to share temperature data, design nested hierarchical monitoring strategies and develop water temperature models to inform managers about all rivers beyond intensively studied sites or catchments.

A better understanding of the impacts of rising water temperature on a larger range of freshwater life considering water temperature, flow changes and interactions with dissolved oxygen would improve awareness of the scale of problem to be managed in future and help identify the most effective measures to achieve multiple environmental objectives.

Identifying simple metrics to determine the likely vulnerability or resilience of river reaches to climate change could inform the choice of planting areas where riparian tree planting is an option. But more understanding is needed to understand the role of other measures available to water managers in the control of water temperature.

The co-production of research that captures perspectives from researchers and river managers is a necessary part of developing adaptation strategies for river ecosystems. Developing crowd sourced, innovative data capture and sharing strategies could help us achieve this. Ideally, the development of an (inter-)national water temperature monitoring community, and the creation of a global repository for temperature data, would greatly enhance understanding and inform the practical management of freshwater systems under a changing climate.

Side bar 1: Keeping Rivers Cool

This initiative involves a range of organisations working together to plan and plant riparian woodland to shade rivers in England. Although pilot catchments were funded, the aim is to utilise and influence other sources of financial support, for example, by better coordination of agriculture and forestry policy instruments. Forestry organisations have a number of woodland for water initiatives, including developing opportunity maps to indicate where woodland can help meet a range of objectives particularly delivery of the EU Water Framework Directive (WFD) objectives[48]. Discussions are underway to include climate change considerations in the targeting of payments in the New Environmental Land Management Scheme (NELMS) in England. There is an intention to build upon the KRC shade maps, to target action and money to river reaches lacking riparian shade cover. If managing water temperature becomes a driver for rural payments, it will be necessary to create tools for river managers to apply the advice and knowledge included in the KRC guidance manual. Socio-economic perspectives could further guide how to practically implement measures across rural and agricultural landscapes.

Acknowledgements

Speakers and attendees at a workshop held in Birmingham on 20th September 2013 are thanked for their contributions to discussion and identification of the research gaps described in section 4. The views of expressed in this paper are those of the authors and do represent the views of the organisations they work for. We also thank two anonymous reviewers whose comments helped improve the paper.

References

1. Jenkins G, Murphy J, Sexton D, Lowe J, Jones P, Kilsby C. UK climate projections: briefing report. Met Office Hadley Centre, Exeter, UK, 2009, 56.

2. Orr HG, Simpson GL, des Clers S, Watts G, Hughes M, Hannaford J, Dunbar MJ, Laizé CLR, Wilby RL, Battarbee RW, Evans R. Detecting changing river temperatures in England and Wales. *Hydrological Processes* 2014. DOI: 10.1002/hyp.10181

3. Hannah DM, Garner G. River water temperature in the United Kingdom: changes over the 20th century and possible changes over the 21st century. *Progress in Physical Geography* 2014, in press.

4. Garner G, Hannah DM, Sadler JP, Orr HG. River temperature regimes of England and Wales: spatial patterns, inter-annual variability and climatic sensitivity. *Hydrological Processes*, 2013. doi: 10.1002/hyp.9992

5. van Vliet MTH, Franssen WHP, Yearsley JR, Ludwig F, Haddeland I, Lettenmaier DP and Kabat P. Global river discharge and water temperature under climate change. *Global Environmental Change* 2013, 23:450–464. doi: 10.1016/j.gloenvcha.2012.11.002

6. Ficke AD, Myrick CA, Hansen LJ. Potential impacts of global climate change on freshwater fisheries. Reviews in Fish Biology and Fisheries 2007, 17(4):581-613.

7. Rahel FJ, Olden JD. Assessing the Effects of Climate Change on Aquatic Invasive Species. Conservation Biology 2008, 22(3): 521–533. doi: 10.1111/j.1523-1739.2008.00950.x

8. Parmesan C. Ecological and evolutionary responses to recent climate change. *Ann. Rev. Ecol. Evol. Syst.,* 2006, 37:637-669. Doi.10.1146/annurev.ecolsys.37.091305.110100

9. Wilby RL, Orr H, Watts G, Battarbee RW, Berry PM, Chadd R, Dugdale SJ, Dunbar MJ, Elliott JA, Extence C, Hannah DM, Holmes N, Johnson AC, Knights B, Milner NJ, Ormerod SJ, Solomon D, Timlett R, Whitehead PJ, Wood PJ. Evidence needed to manage freshwater ecosystems in a changing climate: turning adaptation principles into practice. *Science of the Total Environment* 2010, 408:4150-4164. doi:10.1016/j.scitotenv.2010.05.014

10. Jones ID, Page T, Elliott JA, Thackeray SJ, Heathwaite AL. Increases in lake phytoplankton biomass caused by future climate-driven changes to seasonal river flow. *Global Change Biology* 2011, 17:1809–1820.

11. Walther GR. Community and ecosystem responses to recent climate change. *Phil. Trans. R. Soc. B.* 2010. Doi:10.1098/rstb.2010.0021

12. Vaughan IP, Ormerod JP. Linking interdecadal changes in British river ecosystems to water quality and climatic dynamics. *Global Change Biology,* 2014. doi: 10.1111/gcb.12616

13. Ducharne, A. Importance of stream temperature to climate change impact on water quality, *Hydrol. Earth Syst. Sci*. 2008, 12:797-810. doi:10.5194/hess-12-797-2008

14. Whitehead PG, Wilby RL, Battarbee R, Kernan M, Wade A. A review of the potential impacts of climate change on surface water quality. *Hydrological Sciences Journal* 2009, 54:101–123.

15. Beschta RL. Riparian shade and stream temperature: an alternative perspective. *Rangelands*, 1997, 19(2):25-28.

16. Wilby RL, Johnson MF, Toone JA. Nocturnal water temperatures: Spatial and temporal variations. *Science of the Total Environment* 2014, 482:157-173.

17. JNCC. http://jncc.defra.gov.uk/pdf/Article17Consult_20131010/S1106_UK.pdf (accessed April 14 2014)

18. Webb BW, Hannah DM, Brown LE, Moore RD, Nobilis F. Recent advances in river temperature studies. *Hydrological Processes* 2008, 22:902–918. doi: 10Ð1002/hyp.6994

19. Langan SJ, Johnston UL, Donaghy MJ, Youngson AF, Hay DW, Soulsby C. Variation in river water temperatures in an upland stream over a 30-year period. *Science of the Total Environment* 2001, 265:195-207.

20. Poole GC, Berman CH. An ecological perspective on in-stream temperature: Natural heat dynamics and mechanisms of human-caused thermal degradation. *Environmental Management* 2001, 27:787-802.

21. Brown LE, Cooper L, Holden J, Ramchunder SJ. A comparison of stream water temperature regimes from open and afforested moorland, Yorkshire Dales, northern England. *Hydrological Processes* 2010, 24:3206–3218. doi: 10.1002/hyp.7746

22. Moore RD, Spittlehouse DL, Story A. Riparian microclimate and stream temperature response to forest harvesting: a review. *Journal of the American Water Resources Association* 2005, 41:813–834.

23. Broadmeadow SB, Jones JG, Langford TEL, Shaw PJ, Nisbet TR. The influence of riparian shade on lowland stream water temperatures in southern England and their viability for brown trout. *River Research and Applications* 2010, 27(2):226-237. doi: 10.1002/rra.1354

24. Benyahya L, Caissie D, Satish MG, El-Jabi N. Long-wave radiation and heat flux estimates within a small tributary in Catamaran Brook (New Brunswick, Canada). *Hydrological Processes* 2011. doi: 10.1002/hyp.8141

25. Lawton JH, Brotherton PNM, Brown VK, Elphick C, Fitter AH, Forshaw J, Haddow RW, Hilborne S, Leafe RN, Mace GM, Southgate MP, Sutherland WA, Tew TE, Varley J, Wynne GR. Making Space for Nature: a review of England's wildlife sites and ecological network. Report to Defra, UK, 2010.

26. HM Government. The National Adaptation Programme: making the country resilient to a changing climate. The Stationery Office, London, 2013, 182.

27. Hansen LJ, Biringer JL, Hoffman JR. Buying time: a user's manual for building resistance and resilience to climate change in natural systems. WWF Climate Change Program, 2003, 244.

28. NorWeST: http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html (accessed September 29 2014)

29. Johnson MF, Wilby RL, Toone JA. Inferring air-water temperature relationships from river and catchment properties. *Hydrological Processes* 2014, 28**:**2912-2928. doi:10.1002/hyp.9842

30. Malcolm IA, Hannah DM, Donaghy MJ, Soulsby C, Youngerson AF. The influence of riparian woodland on the spatial and temporal variability of stream water temperatures in an upland salmon stream. *Hydrology and Earth System Science* 2004, 8(3):449-459.

31. Rutherford JC, Marsh NA, Davies PM, Bunn SE. Effects of patchy shade on stream water temperature: how quickly do small streams heat and cool? *Marine and Freshwater Research* 2004, 55:737–748. doi.org/10.1071/MF04120

32. Torgersen CE, Faux RN, McIntosh BA, Poage NJ, Norton DJ. Airborne thermal remote sensing for water temperature assessment in rivers and streams. *Remote Sensing of Environment* 2001, 76(3):386-398.

33. Selker JS, Thévenaz L, Huwald H, Mallet A, Luxemburg W, van de Giesen N, Stejskal M, Zeman J, Westhoff M, Parlange MB. Distributed fiber-optic temperature sensing for hydrologic systems." *Water Resour. Res* 2006, 42: W12202. doi: 10.1029/2006WR005326

34. Isaak DJ, Peterson E, Hoef JV, Wenger S, Falke J, Torgersen C, Sowder C, Steel A, Fortin MJ, Jordan C, Reusch A, Som N, Monestiez P. Applications of spatial statistical network models to stream data. *Wiley Interdisciplinary Reviews: Water* 2014, 1(3):277-294. doi: 10.1002/wat2.1023.

35. http://www.luten.org.uk/home (accessed April 14 2014)

36. Bishop K, Buffam I, Erlandsson M, Fölster J, Laudon H, Seibert J, Temnerud J. Aqua Incognita: the unknown headwaters. *Hydrological Processes* 2007, 22:1239-1242.

37. Everall NC, Johnson MF, Wilby RL, Bennett CJ. Detecting phenology change in the mayfly *Ephemera danica*: Responses to spatial and temporal water temperature variation. *Ecological Entomology*, in press.

38. Bowler DE, Mant R, Orr HG, Hannah DM, Pullen AS. Effects of wooded riparian strips on stream temperature. Systematic review. *Environmental Evidence* 2012, 1:3. doi:10.1186/2047-2382-1-3

39. Garner G, Malcolm IA, Sadler JP, Millar CP, Hannah DM. Inter-annual variability in the effects of riparian woodland on micro-climate, energy exchanges and water temperature of an upland Scottish stream. *Hydrological Processes*, 2014. DOI: 10.1002/hyp.10223.

40. Isaak DJ, Luce C, Rieman BE, Nagel D, Peterson E, Horan D, Parkes S, Chandler G. Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network. *Ecological Applications*, 2010, 20:1350-1371.

41. Handcock RN, Torgersen CE, Cherkauer KA, Gillespie AR, Tockner K, Faux RN, Tan J. Thermal Infrared Remote Sensing of Water Temperature in Riverine Landscapes. In Carbonneau PE, Piégay H eds. Fluvial Remote Sensing for Science and Management, John Wiley & Sons, Ltd, Chichester, UK, 2012. doi: 10.1002/9781119940791.ch5

42. U.S. EPA. Best Practices for Continuous Monitoring of Temperature and Flow in Wadeable Streams (Final Report). U.S. Environmental Protection Agency, Office of Research and Development, National Center for Environmental Assessment, Washington, DC, EPA/600/R-13/170F, 2014.

43. Johnson MF, Wilby RL. Shield or not to shield: Effects of solar radiation on water temperature sensor accuracy. Water (Switzerland) 2013, 5(4):1622-1637. doi: 10.3390/w5041622

44. Thackeray SJ, Sparks TH, Frederiksen M, Burthe S, Bacon PJ, Bell JR, Botham MS, Brereton TM, Bright PW, Carvalho L, Clutton-Brock T, Dawson A, Edwards M, Elliott JM, Harrington R, Johns D, Jones ID, Jones JT, Leech DI, Roy DB, Scott WA, Smith M, Smithers RJ, Winfield IJ, Wanless S. Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments. *Global Change Biology* 2010, 16:3304-3313.

45. Verdonschot RCM, Van Oosten-Siedlecka AM, Besse-Lototskaya A, Verdonschot PFM, Johnson R, Kristensen EA, Lorenz A, Martí E, Angels Puig M, Romero C, García L, Hershkovitz Y. Effects of shading on stream water temperature and stenothermic macroinvertebrates: a synthesis of findings along the trans-European latitudinal climate gradient. REFRESH Collaborative Project Report. http://www.refresh.ucl.ac.uk/Deliverable+2.12_abstract (accessed April 14 2014)

46. Reed MS, Stringer LC, Fazey I, Evely AC, Kruijsen JHJ. Five principles for the practice of knowledge exchange in environmental management. *Journal of Environmental Management*, 2014, 337-345.doi.org/10.1016/j.jenvman.2014.07.021

47. IPCC. Climate Change 2014: Impacts, Adaptation and Vulnerability The Summary for Policymakers of the Working Group II contribution to the Fifth Assessment Report IPCC on 30 March 2014

48. Everall NC, Farmer A, Heath AF, Jacklin TE, Wilby RL. Ecological benefits of creating messy rivers. *Area*, 2012, 44:470-478.

49. Gurnell AM, Gregory KJ, Petts GE. The role of coarse woody debris in forest aquatic habitats: Implications for management. *Aquatic Conservation: Marine and Freshwater Ecosystems* 1995, 5(2): 143–166. doi: 10.1002/aqc.3270050206

50. Osborne LL, Kovacic DA. Riparian vegetated buffer strips in water-quality restoration and stream management. *Freshwater Biology* 2006, 29(2):243–258.doi: 10.1111/j.1365-2427.1993.tb00761.x

51. Simon A, Collison AJC. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. *Earth Surface Processes and Landforms* 2002, 27(5):527–546. doi: 10.1002/esp.325

52. Kristensen PB, Kristensen E A, Riis T, Baisner A J, Larsen SE, Verdonschot PFM, Baattrup-Pedersen A. Riparian forest as a management tool for moderating future thermal conditions of lowland temperate streams. *Hydrol. Earth Syst. Sci. Discuss*, 2013,10:6081–6106.doi: 10.5194/hessd-10-6081-2013

53. Burrell, TK, O'Brien JM, Graham SE, Simon KS, Harding JS, McIntosh AR. 2014. Riparian shading mitigates stream eutrophication in agricultural settlements. *Freshwater Science,* 2014, 33(1):73-84. Doi: 10.1086/674180.

54. http://www.theriverstrust.org/catchment_mapping/index.html (accessed April 11 2014)

55. Coley A, Pettit L, McMellin G. Detailed River Network (DRN) data description and guide document: detailed description and user guide of a general purpose, high-resolution Environment Agency Detailed River Network (DRN) at release 1. Environment Agency report code 6721, 2008.

56. http://www.climatecentral.org/news/white-house-brings-together-big-data-and-climate-change-17194

Figure captions

Figure 1: Conceptual impact of some catchment variables on stream temperature from catchment headwaters to outlets (adapted from Poole & Berman, 2001).

Figure 2: Amount and distribution of riparian tree cover in England and Wales presented as an average percentage cover for all river units defined as water bodies under the EU WFD [white areas represent missing data].

Tables

Table 1 River length and stream order in England and Wales

Strahler Stream Order	River length (km)	% of all river length
1	116531	43
2	67775	25
3	39756	15
4	23078	8
5	13272	5
6	7108	3
7	3209	1
8	1182	<1

Table 2 Critical research questions to support thermal management of rivers

Understanding thermal refugia
• How far downstream does shading by riparian vegetation provide thermal benefits? • What are the most effective techniques for mapping thermal refugia (remote sensing, fluvial audit, high-resolution thermistor arrays)? • How many refugia are needed to protect target species? • How might tagging be used to better understand refugia distribution and use by biota?
Understanding water temperature variations
• What are the impacts of artificial structures (such as weirs, flood defences, etc.) on the thermal dynamics of rivers? • How effective is shading in heavily modified and/or urban streams? • How do river restoration, abstraction, water level and in-river structure management affect temperature? • What site and catchment factors determine the efficacy of shade management? • How can detailed site-specific process studies be up-scaled to catchment characterisation or transferred to other rivers?
Understanding warming impacts on in-stream ecosystems
• What thermal regime metrics are most useful for detecting and attributing change then informing management of water temperature? • What is the relative significance of direct and indirect (e.g. dissolved oxygen levels) impacts of water temperature on biota? • What thermal parameters are of most biological significance, recognising that this is animal specific and that knowledge is presently restricted to a few species? • What are the potential direct and indirect consequences of climate change for the function and structure of riparian buffer strips?

Related Articles

DOI	Article title
DOI: 10.1002/wat2.1021	The changing nature of river restoration
doi: 10.1002/wat2.1023.	Applications of spatial statistical network models to stream data

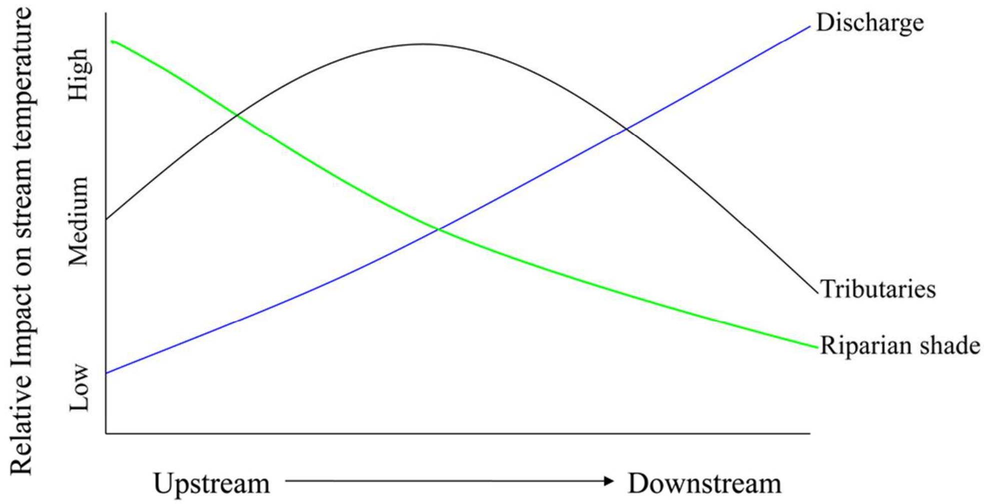

Figure 1: Conceptual impact of some catchment variables on stream temperature from catchment headwaters to outlets (adapted from Poole & Berman, 2001).
84x47mm (300 x 300 DPI)

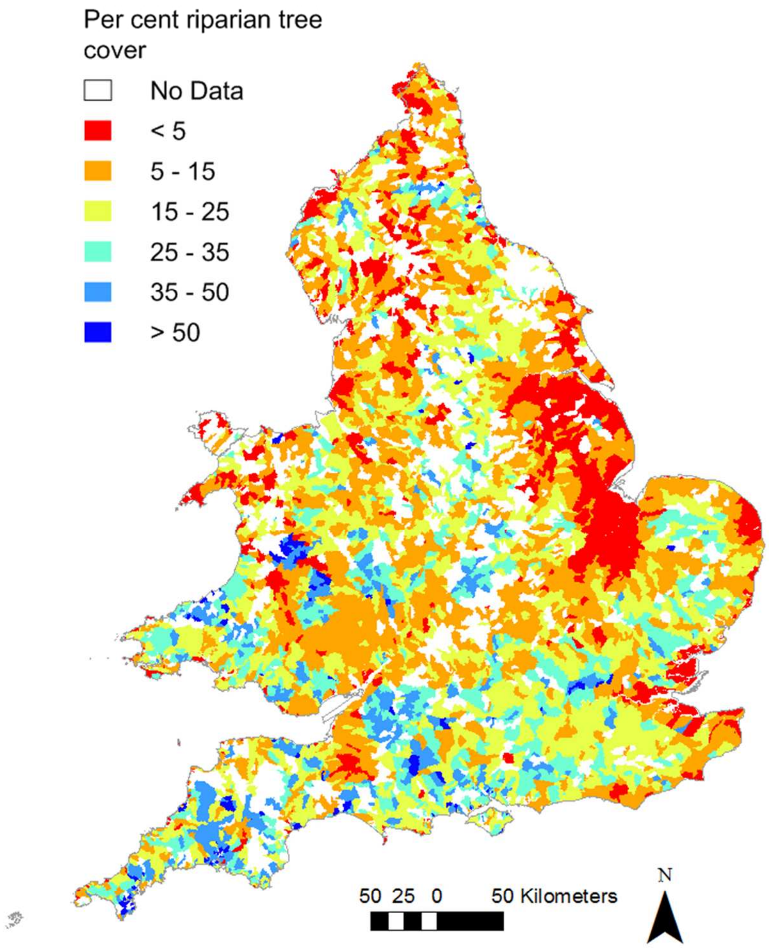

Figure 2: Amount and distribution of riparian tree cover in England and Wales presented as an average percentage cover for all river units defined as water bodies under the EU WFD [white areas represent missing data].
210x297mm (96 x 96 DPI)