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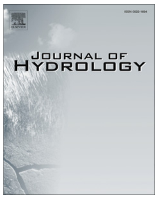

Research papers

The role of riparian vegetation density, channel orientation and water velocity in determining river temperature dynamics

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ABSTRACT

A simulation experiment was used to understand the importance of riparian vegetation density, channel orientation and flow velocity for stream energy budgets and river temperature dynamics. Water temperature and meteorological observations were obtained in addition to hemispherical photographs along a ~1 km reach of the Girnock Burn, a tributary of the Aberdeenshire Dee, Scotland. Data from nine hemispherical images (representing different uniform canopy density scenarios) were used to parameterise a deterministic net radiation model and simulate radiative fluxes. For each vegetation scenario, the effects of eight channel orientations were investigated by changing the position of north at 45° intervals in each hemispheric image. Simulated radiative fluxes and observed turbulent fluxes drove a high-resolution water temperature model of the reach. Simulations were performed under low and high water velocity scenarios. Both velocity scenarios yielded decreases in mean ($\geq$1.6 °C) and maximum ($\geq$3.0 °C) temperature as canopy density increased. Slow-flowing water resided longer within the reach, which enhanced heat accumulation and dissipation, and drove higher maximum and lower minimum temperatures. Intermediate levels of shade produced highly variable energy flux and water temperature dynamics depending on the channel orientation and thus the time of day when the channel was shaded. We demonstrate that in many reaches relatively sparse but strategically located vegetation could produce substantial reductions in maximum temperature and suggest that these criteria are used to inform future river management.

1. Introduction

It is anticipated that a changing climate will alter river temperature regimes. Elevated temperatures relative to historical baselines are expected for most watercourses (e.g. Beechie et al., 2013; van Vliet et al., 2013; MacDonald et al., 2014a; Hannah and Garner, 2015). Such changes, particularly increased maxima, may diminish the spatial and temporal extent of suitable cool-water habitat for temperature sensitive organisms with potential impacts on the composition and productivity of aquatic ecosystems (Wilby et al., 2010; Leach et al., 2012). Consequently, there is substantial interest in adaptation strategies that may ameliorate the effects of climate warming, including: riparian planting (e.g. Hannah et al., 2008; Brown et al., 2010; Imholt et al., 2013; Ryan et al., 2013; Garner et al., 2014), reconnecting rivers to their floodplains (e.g. Poole et al., 2008; Opperman et al., 2010), restoring or enhancing hyporheic exchange (Beechie et al., 2013; Kurylyk et al., 2014), reducing and retaining urban runoff (e.g. Booth and Leavitt, 1999) and reducing rates of water abstraction (Poole and Berman, 2001). However in upland streams, where catchment hydrology and geomorphology have not been altered significantly by human activities, fewer of these strategies may be implemented to protect aquatic ecosystems from thermal extremes (Beschta, 1997; Poole and Berman, 2001). Observational datasets, frequently in combination with deterministic modelling approaches, have demonstrated that the summer temperature of headwater streams is generally dominated by: (1) advected heat from upstream (2) heat exchange at the air–water column interface (e.g. Westhoff et al., 2011; Leach and Moore, 2014; MacDonald et al., 2014a; Garner et al., 2014), predominantly solar radiation gains (Hannah et al., 2008; Leach and Moore, 2010; MacDonald et al., 2014a), and at some locations (3) groundwater inflows (e.g. Westhoff et al., 2007). Recognising the important role of energy exchange between the atmosphere and the water column and in response to the increasing scientific literature, river managers (e.g. The River Dee Trust; Upper Dee riparian scheme) are increasingly advocating the use of riparian vegetation to reduce total energy inputs to the water column,

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and thus thermal variability and extremes (e.g. Gomi et al., 2006; Johnson and Jones, 2000; Hannah et al., 2008; Imholt et al., 2011, 2013; Garner et al., 2015).

Although there is a clear requirement for understanding the effects of riparian cover on stream temperature, there have been relatively few robust process based studies that provide realistic predictions of the likely effects of land use change. Moore et al. (2014) discussed various methods for representing the effects of vegetation on radiative energy fluxes above streams. However, to date river temperature models (e.g. Rutherford et al., 1997; Watanabe et al., 2005; DeWalle, 2008; Roth et al., 2010; Lee et al., 2012) have not considered the importance of vegetation structure (i.e. leaves, trunks and branches) and location relative to the position of the sun and the receiving waterbodies. Therefore, they were unable to adequately account for the temporally variable influence of discontinuous vegetation on the radiation budget. Furthermore, vegetation also has a significant effect on riparian microclimatic variables such as wind speed, relative humidity and air temperature, resulting in large reductions in latent heat losses (e.g. 60–87% was observed by Garner et al., 2015) in comparison to open reaches (e.g. Hannah et al., 2008; Garner et al., 2015). However, most modelling studies (e.g. Rutherford et al., 1997; Watanabe et al., 2005; DeWalle, 2008; Lee et al., 2012) have not considered the effects of changing microclimate as a result of riparian landuse change and so likely over-estimated the effect of forest canopies on reducing net energy fluxes and thus water temperature. Consequently, attempts to simulate the effects of riparian landuse change on water temperature have lacked the necessary physical realism to produce accurate estimates of effect sizes.

This study aims to generate systematic, process-based information on the effects of: (1) channel shading, (2) channel orientation and (3) water velocity on river temperature. Previous modelling and observational studies suggest that these three variables play an important role in determining river temperature dynamics. Firstly, because water temperatures are lower when vegetation is present (e.g. Hannah et al., 2008; Hrachowitz et al., 2010; Roth et al., 2010; Garner et al., 2015) and instantaneous differences in temperature between forested and open locations are greatest at sites under the densest canopies (e.g. Roth et al., 2010; Broadmeadow et al., 2011; Groom et al., 2011; Imholt et al., 2013). Secondly, because the orientation of the channel (LeBlanc et al., 1997; DeWalle, 2008; Li et al., 2012) and therefore the location of vegetation relative to the path of the sun is important in controlling solar radiation inputs (Lee et al., 2012). Finally, because longitudinal temperature gradients are reduced in steeper, faster flowing reaches compared with flatter, slower flowing ones (e.g. Danehy et al., 2005; Subehi et al., 2009; Groom et al., 2011). Knowledge of these controls and their interactions is important to inform optimal tree planting strategies and to assess likely outcomes.

In this context, we simulate the effects of varying riparian vegetation density and channel orientation on the stream energy budget and quantify their influence on water temperature dynamics under scenarios of high and low water velocity. The effects of riparian vegetation on river temperature are modelled using hemispheric photographs of different riparian canopy densities under field observed conditions and local measurements of micro-climate, thereby providing improved realism to estimates of likely effect size while at the same time being sufficiently generalisable to provide useful information to inform riparian planting strategies.

2. Study area

We collected field data within a 1050 m study reach of Glen Girnock. This upland basin is located in north east Scotland and drains into the Aberdeenshire Dee (Fig. 1). The catchment upstream of the reach has an area of ~22 km^2 in which heather (*Calluna*) moorland dominated landuse. Riparian landuse along the reach transitioned from moorland to semi-natural forest composed of birch (*Betula*), Scots pine (*Pinus*), alder (*Alnus*) and willow (*Salix*) (Imholt et al., 2010). Basin soils are composed predominantly of peaty podsols with some peaty gleys. Basin geology is dominated by granite at higher elevations and schists at lower elevations and is thus relatively impermeable (Tetzlaff et al., 2007). Within the study reach the riverbed is composed primarily of cobble and boulder with gravel accumulation in localised patches. The reach is 280 m above sea level (asl) at the upstream reach boundary and 255 m asl at the downstream reach boundary. During field data collection the mean wetted width of the channel was 9.5 m. Previous work within the study reach demonstrated that there are no substantial groundwater inflows and consequently that groundwater does not significantly modify water temperature dynamics (Malcolm et al., 2005; Garner et al., 2014). Thus, the influence of canopy density, channel orientation and water velocity on water temperature could be investigated in the absence of confounding groundwater influences (e.g. Story et al., 2003; Westhoff et al., 2011).

The UK Meteorological Office record daily averages of air temperature and totals of precipitation at Balmoral (<10 km north west of the catchment). During the period 1950–2013 annual average air temperature was 6.6 °C, maximum temperatures occurred in June and July (daily averages 13.0 and 12.6 °C respectively) and minima occurred in December to February (daily averages 2.4, 2.2 and 1.6 °C respectively). Between 1950 and 2013 annual average precipitation totalled 846 mm, October to January were the wettest months (daily average totals ranged from 85.7 mm in December to 92.5 mm in October) and February to September were the driest (daily average totals ranged from 55.1 mm in April to 70.8 mm in August). River discharge is monitored continuously by the Scottish Environmental Protection Agency (SEPA) in a rated natural section of the Girnock at Littlemill (Fig. 1). Annual mean flow is 0.530 m^3 s^{-1} (1969–2013). Summer flows (i.e. June-August) are typically <0.100 m^3 s^{-1} but the flow regime is highly responsive to precipitation and so high flow events (e.g. $\geq Q_{10}$, 1.126 m^3 s^{-1}) occur year-round.

3. Methods

3.1. Experimental design

Spatially distributed field data were used to parameterise a simulation experiment that investigated the influence of: (1) riparian vegetation density, (2) channel orientation (and thus vegetation orientation relative to the sun's path), and (3) water velocity (a proxy for stream gradient) on heat exchange patterns and water temperature dynamics within a 1050 m reach of the Girnock Burn. A single time series of discharge was used for each velocity scenario thereby separating the effects of velocity and residence time from those of varying water volume. Consequently, the effects of each vegetation and channel orientation scenario were simulated for a low (i.e. slow velocity: 0.023 ms^{-1}) or high gradient (i.e. fast velocity: 0.155 ms^{-1}) river. We did not investigate the effects of changing discharge because we were primarily interested in the effects of riparian woodland on river temperature under summer low flow conditions, when the most extreme high water temperatures are expected to occur.

Firstly, a process-based water temperature model (herein referred to as the 'base model') driven by spatially distributed energy flux data temperature (Garner et al., 2014 after Bartholow, 2000; Boyd and Kasper, 2003; Rutherford et al., 2004; Westhoff et al., 2007, 2010; Leach and Moore, 2011; MacDonald et al., 2014a,b) was parameterised for observed conditions within the Girnock Burn. Previous work suggested that the base model