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Low flow controls on stream thermal dynamics

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ABSTRACT

Water level fluctuations in surface water bodies, and in particular low flow drought conditions, are expected to become more frequent and more severe in the future due to the impacts of global environmental change. Variations in water level, and therefore in-channel water volume, not only have the potential to directly impact stream temperature, but also aquatic vegetation coverage which, in turn, may affect stream temperature patterns and dynamics. Manipulation experiments provide a systematic approach to investigate the multiple environmental controls on stream temperature patterns. This study aims to use temperature data loggers and fibre optic distributed temperature sensing (FO-DTS) to investigate potential drought impacts on patterns in surface water and streambed temperature as a function of change in water column depth. To quantify the joint impacts of water level and associated vegetation coverage on stream temperatures, investigations were conducted in outdoor flumes using identical pool-riffle-pool features, but with spatially variable water levels representative of different drought severity conditions. Naturally evolved vegetation growth in the flumes ranged from sparse vegetation coverage in the shallow flumes to dense colonization in the deepest. Observed surface water and streambed temperature patterns differed significantly within the range of water levels and degrees of vegetation coverage studied. Streambed temperature patterns were more pronounced in the shallowest flume, with minimum and maximum temperature values and diurnal temperature variation being more intensively affected by variation in meteorological conditions than daily average temperatures. Spatial patterns in streambed temperature correlated strongly with morphologic features in all flumes, with riffles coinciding with the highest temperatures, and pools representing areas with the lowest temperatures. In particular, the shallowest flume (comprising multiple exposed features) exhibited a maximum upstream-downstream temperature warming of 3.3 °C (T in = 10.3 °C, T out = 13.5 °C), exceeding the warming observed in the deeper flumes by ~2 °C. Our study reveals significant streambed and water temperature variation caused by the combined impacts of water level and related vegetation coverage. These results highlight the importance of maintaining minimum water levels in lowland rivers during droughts for buffering the impacts of atmospheric forcing on both river and streambed water temperatures.

1. Introduction

Temperature is a master water quality variable driving physical, chemical, and biological processes in aquatic ecosystems by directly influencing metabolic rates, physiology and life-history traits of aquatic organisms, as well as their abundance and distribution (Webb, 1996; Constantz, 1998; Bogan et al., 2003; Caissie, 2006; Webb et al., 2008). Stream water temperature is dynamic over space and time (Poole and Berman, 2001), and is influenced by numerous natural variables and eco-hydrological processes, including solar radiation, air temperature, heat transfer at the air-water interface, precipitation, riparian vegetation shading, surface water inflows, and groundwater and streambed

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heat exchanges (Constantz, 1998; Bogan et al., 2003; Johnson, 2004; Arrigoni et al., 2008; Webb et al., 2008; Garner et al., 2015a; Hannah and Garner, 2015). In particular, the streambed, identified as an important heat source and sink (Evans et al., 1998; Hannah et al., 2004), can significantly affect the river's energy budget both temporally and spatially (Evans et al., 1998), influencing water column temperatures. Natural temporal fluctuations in surface and streambed water temperature are observed on a diel and annual cycle (Caissie, 2006), while spatially, temperatures generally increase along the longitudinal dimension. However, discontinuities, both of natural and anthropogenic origin can interrupt the longitudinal thermal profile (Fullerton et al., 2015). At the micro-scale, morphological in-stream structures like riffle-pool sequences create spatial temperature heterogeneity, supporting diverse communities and providing refuge from extreme temperatures, especially during summer (Hester et al., 2009; Dallas and Rivers-Moore, 2011). Although temperature variations occur naturally, river flow and thermal regimes have been profoundly altered by both climate change and human interventions, *e.g.* dams and water withdrawals, on the hydrological cycle (Döll and Zhang, 2010; Schneider et al., 2013; Laizé et al., 2014), with potential severe impacts on freshwater ecosystems and biodiversity (Bates et al., 2008; Bond et al., 2008; Poff and Zimmerman, 2010; Vörösmarty et al., 2010).

Extreme climatic events have recently received attention (Easterling et al., 2000; Garner et al., 2015b; Ledger and Milner, 2015; Leigh et al., 2015) because of the growing awareness that they may cause dramatic changes to river and streambed temperature regimes (Jentsch et al., 2007; Palmer et al., 2009). Droughts, in particular, can lead to a decrease in flow permanence (Lake, 2003), fragmenting the water course into pools (Boulton, 2003), possibly drying the streambed, and reducing longitudinal connectivity (Bogan et al., 2015). As a consequence of these drought effects, water quality generally declines and surface water temperatures increase (Matthews, 1998). As most aquatic organisms are ectotherms (Giller and Malmqvist, 1998), and thus, are sensitive to increases in water temperatures (Daufresne et al., 2009), understanding how water level fluctuations control river and streambed thermal regimes has become indeed a matter of urgency to assure aquatic ecosystem integrity and functioning.

Water depth together with discharge and velocity directly influences and regulates the distribution and growth of aquatic flora (Riis and Biggs, 2003; Franklin et al., 2008; Bornette and Puijalon, 2011). Macrophyte communities play a key role in unshaded streams (Riis and Biggs, 2003), by increasing physical and biological diversity, and by contributing to habitat structure and ecological functioning of these systems (Warfe and Barmuta, 2006; Thomaz and Cunha, 2010). While stable flows favour macrophyte biomass (Mebane et al., 2014), the increased number and frequency of hydrological disturbance events, such as floods and droughts, can significantly alter the composition and abundance of aquatic macrophyte communities (Riis and Biggs, 2001; Riis and Biggs, 2003; Stromberg et al., 2005), causing biomass destruction, and habitat structure change (Grime, 1979). Under this constraint, plant species with a greater resistance and/or resilience usually dominate (Riis et al., 2008), whereas others, such as *Ranunculus* species, only occupy channel areas with permanent flow (Westwood et al., 2006). As a result, during droughts, the channels of ephemeral or perennial streams experiencing severe drying can be invaded and colonized by resistant and/or amphibian or riparian plant species (Bunn and Arthington, 2002; Lake, 2003), a process called terrestrialization (Westwood et al., 2006; Holmes, 1999). Strictly aquatic macrophytes (Schuyler, 1984) and non-aquatic forms possess different shading abilities that are quite influential for both water and streambed temperatures. Non-aquatic forms in particular, being characterized by more competitive growth forms (*e.g.* tall or broad-leafed species; Bornette and Puijalon, 2011), have highly variable shading effects on surface water and streambed sediments. Therefore, water level fluctuations due to drought conditions can influence aquatic vegetation coverage and indirectly, stream temperature regimes. However, to our knowledge, no previous high spatio-temporal resolution studies of the combined impact of both water level and vegetation coverage on temperatures at the channel bed and in the water column have been carried out.

Direct *in situ* studies of water level impacts on the thermal regime of natural channels can be challenging technically and logistically because of their high spatial and temporal complexity. The use of distributed fibre optic monitoring solutions allow for the possibility to investigate stream thermal regimes continuously in both time and space (Selker et al., 2006b; Tyler et al., 2009). In this way, high spatial and temporal stream temperature variability can be detected, resulting in improved monitoring and assessment of stream thermal regimes. Manipulating water levels in a flume experimental set-up allows for the isolation and alteration of the key variables of interest under controlled conditions, although at a smaller physical scale (Mosley and Zimpfer, 1978).

The aim of this study was to analyse the combined effect of water level variation and co-evolved vegetation coverage on the streambed and surface temperature patterns of artificial rivers. Using three outdoor flumes, representative of characteristic lowland gravel-bed rivers with developed plant communities, the potential drought (*e.g.* water level) impacts on the downstream warming of surface water and spatial patterns of streambed surface temperatures were assessed continuously for the duration of the study. Temperature data loggers coupled with high-resolution fibre optic distributed temperature sensing (FO-DTS) technology allowed for the characterisation of surface water and streambed thermal variability responses at unprecedented spatial and temporal scales. We hypothesised that: (i) surface water warming would be inversely associated with water depth with temperatures in the deeper flumes being more effectively buffered by both the water column and broader co-evolving vegetation coverage than in shallower flumes; (ii) spatial temperature patterns would be more pronounced in the shallowest flume with extreme temperature values (maximum and minimum streambed and surface water temperature values) varying more than average temperatures; and (iii) the impact of meteorological variability, especially changes in air temperature and solar radiation, would be more marked for shallower water depths.

2. Material and methods

2.1. Site description

Our experiment used three outdoor flumes at Fobdown Watercress Farm, near New Alresford, Hampshire, U.K. (51°06′08.57″N, 1°11′06.33″W, 99 m asl; Fig. 1).

The experiment ran from ~16:00 23-04-2014 to ~14:00 25-04-2014. Average air temperature for the month of April was 10.0 °C (Alice Holt Lodge UK Met Office weather station, ~30 km away from study site), with a peak of 17.5 °C on the 21-04-14. The minimum of 2.1 °C was registered the 24-02-16. Daily average precipitation was 0.2 mm with a maximum of 13.4 mm on the 25-04-14 (Fig. 2).

The aluminium flumes had dimensions of 15 m length and 0.5 m width, with walls of 0.5 m (Fig. 1). Water supply for the flumes was provided from a groundwater well with a constant temperature of 10.1 °C. Water quality parameters (temperature, electric conductivity and dissolved oxygen) were monitored continuously to ensure stationary water quality boundary conditions throughout the experiment. Groundwater (GW) was pumped at a constant rate into a feeder tank of 80 L capacity, from where it was subsequently distributed to the flumes using a network of pipes. Different water levels were obtained by regulating the water intake and outflow for each flume separately, and water levels in the pools were set to 25, 10 and 7 cm in the three flumes, respectively (flumes are hereafter referred to as '1_25 cm', '2_10 cm' and '3_07 cm'). The three water levels were representative of different levels of drought severity, with flume 1_25 cm representing close to normal flow conditions for southern UK chalk streams, flume 2_10 cm summer low flow conditions and 3_07 cm severe drought conditions. Steady state conditions were maintained throughout the experiment.