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WATER TEMPERATURE PATTERNS BELOW LARGE GROUNDWATER SPRINGS: MANAGEMENT IMPLICATIONS FOR COHO SALMON IN THE SHASTA RIVER, CALIFORNIA

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ABSTRACT

Elevated stream temperature is a primary factor limiting the coho salmon (*Oncorhynchus kisutch*) population in California's Shasta River Basin. Understanding the mechanisms driving spatial and temporal trends in water temperature throughout the Shasta River is critical to prioritising river restoration efforts aimed at protecting this threatened species. During the summer, the majority of streamflow in the Shasta River comes from large-volume, cold-water springs at the head of the tributary Big Springs Creek. In this study, we evaluated the initial character of this spring water, as well as the downstream fate and transport of these groundwater inflows during July and August 2008. Our results indicated that Big Springs Creek paradoxically provided both cool and warm waters to the Shasta River. During this period, cool groundwater inflows heated rapidly in the downstream direction in response to thermal loads from incoming solar radiation. During the night time, groundwater inflows did not appreciably heat in transit through Big Springs Creek. These diurnally varying water temperature conditions were inherited by the Shasta River, producing longitudinal temperature patterns that were out of phase with ambient meteorological conditions up to 23 km downstream. Findings from this study suggest that large, constant temperature spring sources and spring-fed rivers impart unique stream temperature patterns on downstream river reaches that can determine reach-scale habitat suitability for cold-water fishes such as coho salmon. Recognising and quantifying the spatiotemporal patterns of water temperature downstream from large spring inflows can help identify and prioritize river restoration actions in locations where temperature patterns will allow rearing of cold-water fishes. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS: Big Springs Creek; thermal refugia; spring-fed rivers; Klamath River

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INTRODUCTION

Water temperature is an important physical mechanism controlling aquatic ecosystem processes and function in lotic environments. In streams dominated by cold-water fish assemblages, elevated water temperatures are known to limit the longitudinal distribution of fish, force changes in migration patterns, influence growth rates and even cause mortality (Quinn, 2005). Consequently, understanding and ameliorating elevated stream temperature conditions, particularly during the summer, has become a priority water quality objective for fisheries managers throughout the western USA (e.g. USEPA, 2003).

Stream temperature at a given location is largely derived from complex interactions between diverse thermal inputs, including solar radiation, atmospheric exchange across the air–water interface, bed conduction and advective inflows. Water temperature patterns are typically driven by atmospheric conditions, with solar radiation considered a principal component of thermal loading in streams (Sinokrot and Stefan, 1993). The effect of solar radiation on stream temperature is particularly pronounced in small and degraded streams without the buffering capacity of shading vegetation (Johnson and Jones, 2000). Although meteorological conditions (e.g. air temperature or solar radiation) can be used to predict stream temperature dynamics in many streams, recent studies (e.g. Tague *et al*., 2007) highlight the potentially strong influence of advective inputs from cold groundwater sources on thermal regimes and fisheries habitat. For example, groundwater inputs such as hyporheic flow and small lateral springs and seeps can provide local thermal refugia for cold-water fishes but typically do little to alter reach-scale thermal regimes driven by atmospheric conditions (Torgersen *et al*., 1999, Ebersole *et al*., 2001, Sutton *et al*., 2007). However, voluminous cold-water inflows sourced from large groundwater aquifers can strongly influence reach to segment-scale stream temperature conditions and may override ambient thermal influences on stream temperature patterns over large downstream distances (Tague *et al*., 2007).

This study seeks to understand the summertime fate and transport of relatively large volumes of cold groundwater originating at the head of a 3.7 km spring-fed creek and flowing into downstream reaches of the Shasta River in

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northern California (Figure 1). Previous studies (Jeffres *et al*., 2009) have shown that during the late spring and summer, groundwater advected into the spring-fed Big Springs Creek (Figure 1) is the source of most (82%) of the water in downstream reaches of the Shasta River. These cold groundwater inflows have been identified as a potentially important factor in lowering stream temperatures in downstream reaches of the Shasta River (NCRWQCB, 2006, Null *et al*., 2010) where warm late spring and summer water temperatures are the primary factor limiting rearing cold-water salmonid populations and particularly the federally threatened coho salmon (NRC, 2004). Total maximum daily loads for temperature established for the Shasta River (NCRWQCB, 2006) recognize the importance of minimising the heating rate of groundwater-derived streamflow in Big Springs Creek in order to meet established water temperature compliance goals for the Shasta River. However, because of previous land access restrictions, a comprehensive analysis of the thermal characteristics of this large groundwater source as it travels downstream through Big Springs Creek and the Shasta River has been limited.

Temperatures of groundwater inflows into Big Springs Creek are cool (11–12 °C) and nearly invariant (NCRWQCB, 2006, Null *et al*., 2010). Increases in streamflow in Big Springs Creek through modified water management practices are generally assumed to benefit cold-water rearing habitat for coho salmon by improving water temperature conditions downstream in the Shasta River. However, the combination

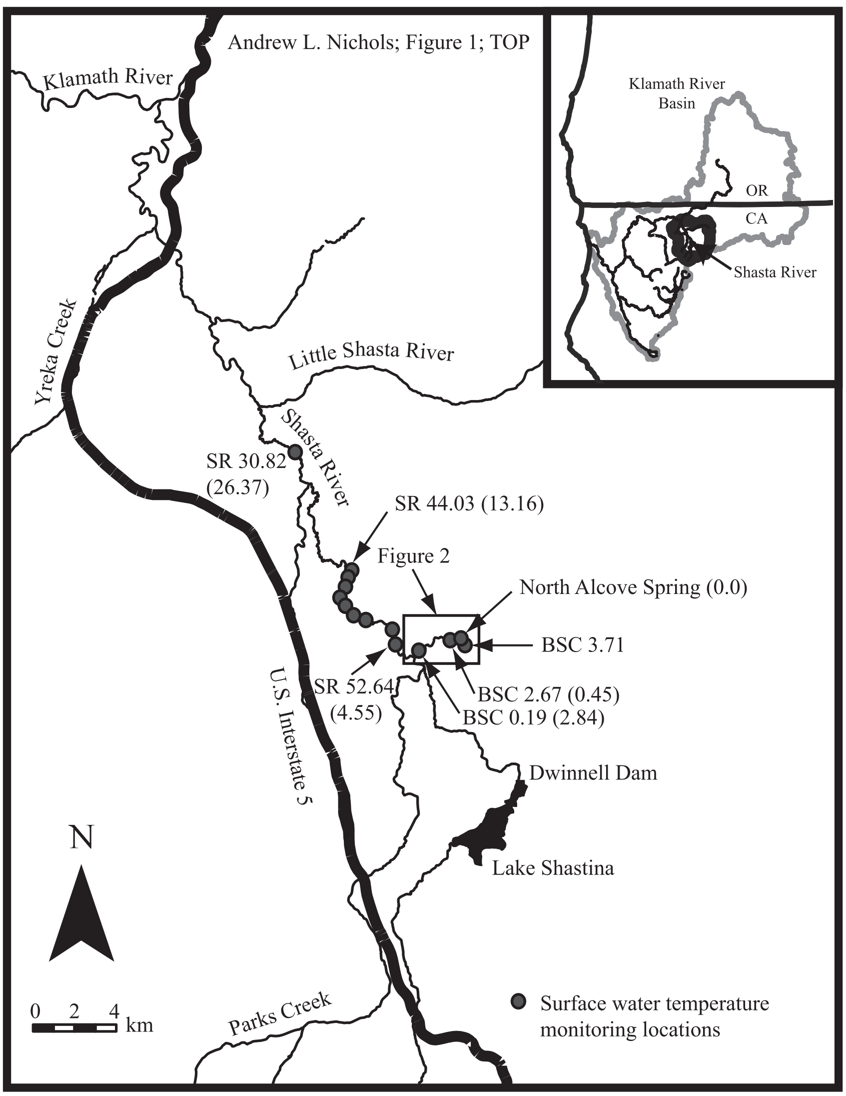

Figure 1. Stream temperature monitoring sites located in the Shasta River Basin, California. Shasta River (SR) and Big Springs Creek (BSC) river kilometer locations (e.g. SR 44.03) and the downstream distance from groundwater spring sources located at the head of Big Springs Creek [e.g. (13.16)] are presented for each temperature logger

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of irrigation infrastructure and decades of unrestricted cattle grazing along and within Big Springs Creek created extraordinarily wide, shallow and unshaded stream conditions that enhanced thermal loading and could raise daytime water temperatures from around 12 °C to almost 25 °C at the confluence with the Shasta River only 3.7 km downstream (Jeffres *et al.*, 2009)—a maximum heating rate of approximately 4 °C/km. Such conditions create an anomalously variable diurnal thermal signal characterized by paradoxically cold and warm inflows into the Shasta River. The objective of this investigation was to understand the fate of these considerable flows of initially cold groundwater as they were conveyed through Big Springs Creek, into the Shasta River, and through downstream reaches. Additionally, this investigation provided an opportunity to collect baseline water temperature data during a short, 1-year period prior to the initiation of planned restoration activities throughout Big Springs Creek in 2009. We compared temporal and spatial variations in stream temperature throughout Big Springs Creek and the Shasta River in July and August 2008 and explored the downstream character of the thermal signal produced by Big Springs Creek during the critical summer rearing season for 0+ coho. Understanding the characteristics and longitudinal effects of inflow groundwater as it flows through Big Springs Creek and subsequently into the Shasta River was an important step towards prioritising restoration and management actions that can maximize the benefits of this large cold-water source by creating more persistent, thermally viable summertime juvenile coho rearing conditions within the Shasta River Basin (NRC, 2004, Jeffres *et al.*, 2009).

GEOGRAPHIC SETTING

The Shasta River is the fourth largest tributary to the Klamath River and the first major tributary downstream from Iron Gate Dam in northern California (Figure 1). The Shasta River flows northwestward across a 2070 km^2 watershed (Figure 1). Upland areas are largely forested, whereas land use in the lowland valley portions is principally irrigated cattle pasture and alfalfa production. The southern and eastern watershed boundaries are dominated by the 4322-m Mount Shasta stratovolcano and several smaller volcanic cinder cones. The western and northern watershed boundaries are formed by the Klamath Mountains, which largely prevent easterly flowing moist air originating over the Pacific Ocean from reaching the Shasta River Valley. Annual precipitation in the basin ranges from 25–46 cm/yr, with precipitation amounts increasing from north to south (NCRWQCB, 2006). Consistent with northern California's Mediterranean climate, most precipitation falls as winter rain and snow.

Streamflow originating in the Klamath Mountains generally follows winter precipitation and spring snowmelt patterns, largely mimicking hydrologic regimes observed in other Mediterranean-montane environments throughout California. Headwater streamflow is routed through a large, low-gradient alluvial valley before entering a steep, 13-km bedrock canyon and discharging into the Klamath River. Groundwater springs and spring-fed tributaries located throughout the southern and eastern portions of the Shasta River Valley augment streamflow (Blodgett *et al.*, 1988, Nathenson *et al.*, 2003). These low elevation (<1100 m) groundwater springs are sourced from high elevation (>2500 m) rainfall and snowmelt percolation through young volcanic materials of the High Cascade geologic province (Blodgett *et al.*, 1988, Nathenson *et al.*, 2003). The porous volcanic materials exhibit very high bulk rock permeabilities due to lava tubes and rubble zones (Blodgett *et al.*, 1988). Groundwater flow paths towards these springs are long and deep, with residence times ranging from 25 to 50 years. Groundwater spring sources provide minimally variant flow volumes to the Shasta River and selected tributaries, resulting in streamflows characterized by groundwater-derived baseflows periodically augmented by rainfall and snowmelt-derived runoff sourced from upstream tributaries.

ECOLOGICAL AND WATER USE SETTING

Because of upstream migratory barriers and generally unavailable or poor habitat conditions in the Klamath River, the Shasta River provides critical spawning and rearing habitat for the federally threatened coho salmon (NRC, 2004). Although the size of historic Shasta River coho salmon runs are not known, they are generally assumed to approach 1000 fish (NRC, 2004). The historical productivity of this coho fishery was derived from nearly ideal habitat conditions created by the presence of large groundwater springs. The prolific historical runs of Chinook salmon (*Oncorhynchus tshawytscha*) in the Shasta River Basin (Wales, 1951) highlight this productivity. Volumetrically stable spring water provided ample water for spawning adult coho in the late fall and early winter, whereas thermally stable spring water provided cool summer and relatively warm winter water temperatures for emerging and rearing juveniles. Further, spring flows rich in geologically derived nutrients (Dahlgren *et al.*, 2010) help support a robust food web (Jeffres *et al.*, 2009) and, combined with ideal thermal conditions, elevated coho growth rates (unpublished data, CADFW).

The decline of the Shasta River coho salmon population is multi-faceted. The construction of Dwinnell Dam in 1928 eliminated access to at least 22% of available spawning habitat (Wales, 1951). Although this habitat loss is an important consideration, channel and bank degradation, surface water diversions and regional groundwater pumping have all contributed to diminishing spawning and

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rearing habitat. However, current coho habitat degradation in the Shasta River is characterized principally through the reduction of thermally viable rearing conditions in the late spring and summer (NRC, 2004). The spatial and temporal extent of poor thermal conditions is largely determined by complex interactions between water use and groundwater spring inflows. Published (Chesney *et al*., 2009) and unpublished data from the California Department of Fish and Wildlife suggest juvenile coho throughout the Shasta River Basin often migrate to stream reaches closer to available cold spring sources (areas known as the "Big Springs" and "Shastina Springs" complexes) as water temperatures elevate during the spring and summer. However, migration barriers (e.g. seasonal flashboard dams) in the Shasta River and its tributaries can prevent coho that initially emerge in the lower portions of the Shasta River from migrating upstream to thermally favourable reaches near the spring complexes, thus forcing these coho to leave the Shasta River for the Klamath River as 0+ juveniles (Jeffres and Moyle, 2012). Shasta River 0+ coho that are forced to migrate into the Klamath River likely have low survival due to generally poor summertime rearing conditions (NRC, 2004, Sutton *et al*., 2007), thus contributing to the decline of the Shasta River coho populations.

During the summer rearing period for junvenile coho salmon (in this case July and August), streamflow in the Shasta River below Dwinnell Dam is derived almost entirely from groundwater sources, the largest of which is the spring-fed tributary Big Springs Creek (Figure 2). Parks Creek, Little Shasta River and other tributaries contribute little to streamflow during this period. Inflows from Big Springs Creek during July and August average approximately 1.5 m^3/s and increase downstream flows in the Shasta River by approximately a factor of five (5) (Nichols *et al*., 2010). Numerous water users divert from the Shasta River downstream from Big Springs Creek, gradually diminishing the magnitude of streamflow in the Shasta River. However, such changes have little effect on the spatial patterns (i.e. timing of minimum and maximum daily temperatures) observed in the Shasta River. Further, field data (Jeffres *et al*., 2009, Nichols *et al*., 2010) indicate that summertime stream temperature conditions at the mouth of Big Springs Creek, as opposed to flow magnitudes in the Shasta River, are the principal driver of water temperature conditions in the Shasta River downstream of the confluence. As such, only the effect of Big Springs Creek water temperatures on downstream Shasta River reaches was explored through this study.

Reaches investigated in this study included the entirety of Big Springs Creek and approximately 23 km downstream in the Shasta River. Big Springs Creek flows 3.7 km through pasture and grazing lands, eventually discharging into the Shasta River, which flows an additional 54.2 km to the Klamath River. Channel conditions in Big Springs Creek are characterized by average slopes of 0.003 and wide and shallow cross-section morphologies, with average and

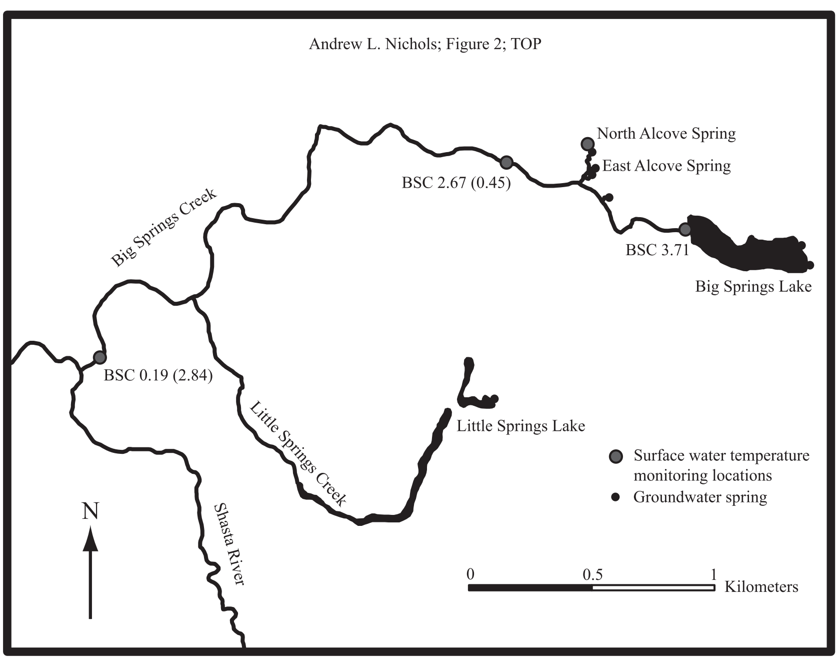

Figure 2. Stream temperature and flow monitoring sites located along Big Springs Creek. Big Springs Lake holds spring water sourced from large groundwater springs located along the lake's eastern edge. The North and East Alcove Springs provide approximately 1.2 m^3/s of 11–12 °C spring water to Big Springs Creek

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Figure 3. Big Springs Creek looking upstream near BSC 0.19. Average bankfull width-to-depth ratio in Big Springs Creek is 84

maximum bankfull width-to-depth ratios of 84 and 237, respectively (Figure 3) (Jeffres *et al*., 2009, Nichols *et al*., 2010). During the period of this study, Big Springs Creek was nearly devoid of shade-providing vegetation, a consequence of poor soil conditions and cattle grazing along the channel margins and within the creek. Although emergent aquatic macrophytes growing in the channel bed of the creek provided partial shading during the summer of 2008, large quantities were removed through unrestricted cattle grazing in the channel (cattle exclusion fencing installed in 2009 has since reduced grazing pressure on in-channel and riparian areas along Big Springs Creek). The Shasta River below Big Springs Creek also flows principally through pasture and grazing land. Channel slopes vary between 0.001 and 0.008, whereas reach-averaged bankfull width-to-depth ratios range from 11 to 29 (Figure 4) (Jeffres *et al*., 2009, Nichols *et al*., 2010)—notably narrower and deeper. Riparian shading along the Shasta River is sparse and does not form a continuous shade feature in the study area (Abbott, 2002). Aquatic macrophyte communities in the Shasta River below Big Springs Creek are dominated by submerged species that do not provide shade.

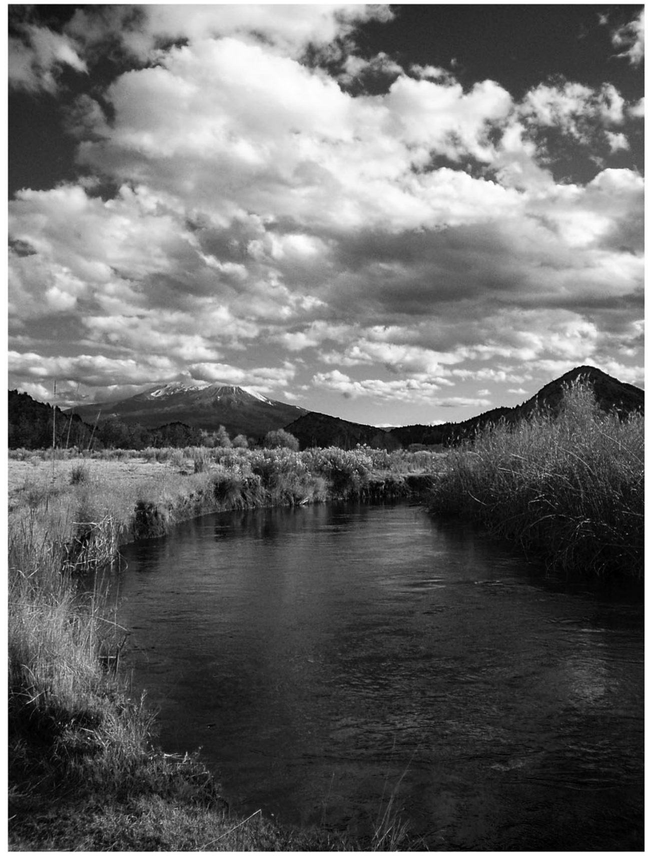

Figure 4. Representative channel reach along the Shasta River downstream from Big Springs Creek

METHODS

Water temperature in discrete groundwater spring sources and throughout Big Springs Creek and the Shasta River was monitored using Onset HOBO Pro v2 loggers at 14 locations (Figures 1 and 2; Table I). Data loggers had a manufacturer-reported accuracy of approximately 0.2 °C and were typically deployed with 0.5 h sampling intervals (water temperature data at BSC 2.67 was collected at a 1.0-h sampling interval). Prior to deployment, data loggers were placed in a water bath of known temperature, and recorded data accuracy was verified. Data loggers were placed in spring heads or on the bed of the stream within protective steel casings. Stream temperature data from July to August 2008 were analysed to assess daily and summer season variation at each monitoring location and to identify longitudinal trends in stream temperature patterns and rates of heating. To assess daily variation at each logger location, daily mean, minimum, maximum and standard deviation were calculated. Spatial temperature variation was assessed using daily temperature means, maxima and minima averaged from July to August. Rates of downstream heating (°C/km) were calculated by dividing the difference between daily maximum, minimum and/or mean summertime stream temperatures measured by two monitoring devices, divided by the distance between the two monitoring locations.

RESULTS

The large ratio of flow in Big Springs Creek relative to upstream sources of flow suggests stream temperature patterns in the Shasta River during the summer were principally driven by advective thermal loads from Big Springs Creek. We will begin by describing the character and fate of

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Table I. Stream temperature monitoring locations

Stream temperature datalogger ID	Downstream distance from spring source (km) [c]	Northing (UTM)	Easting (UTM)
Discrete source springs			
North Alcove spring	0[b]	4605729.736	548813.754
Big Springs Creek			
BSC 3.71	0[a]	4605424.287	549211.334
BSC 2.67	0.45	4605724.484	548349.487
BSC 0.19	2.84	4604913.800	546852.757
Shasta River			
SR 52.64	4.55	4605358.401	545744.858
SR 51.68	5.51	4606221.065	545626.350
SR 49.79	7.40	4606562.077	544204.551
SR 49.41	7.78	4606602.951	543881.938
SR 48.23	8.96	4607111.686	543551.662
SR 47.12	10.07	4607239.782	543042.197
SR 45.9	11.29	4608038.284	543239.633
SR 44.85	12.34	4608685.334	543425.391
SR 44.03	13.16	4609060.829	543365.714
SR 30.82	26.37	4614710.489	540258.578

[a]BSC 3.71 is located at the outfall of Big Springs Lake Dam, behind which groundwater springs are impounded.
[b]The North Alcove spring is located approximately 0.5 km downstream from Logger BSC 3.71.
[c]Distance downstream from North Alcove spring. UTM, Universal Transverse Mercator coordinate system (Zone 10N).

groundwater-derived streamflow through Big Springs Creek and then look at the effect this flow had on temperature patterns along downstream reaches of the Shasta River during July and August 2008. The paper concludes with a hypothesis of how restoration efforts may change this. Similar to previous observations (NCRWQCB, 2006), Big Springs Creek provided both cool and warm waters to the Shasta River. During the daytime, cool groundwater inflows from the headwaters of Big Springs Creek heated rapidly in the downstream direction in response to meteorological conditions and principally thermal loads from incoming solar radiation. During the nighttime, groundwater inflows did not appreciably heat in transit through Big Springs Creek. These diurnally varying water temperature conditions had direct implications for water temperature patterns in Shasta River reaches up to 23 km downstream. Useful to subsequent discussions of water temperature pattern in Big Springs Creek and the Shasta River is an understanding of equilibrium temperature (see Bogan *et al*., 2003), which is a specific temperature of a water body at which the net heat exchange is 0. When the equilibrium temperature is reached, the temperature of the water body stops changing until it is exposed to a different set of meteorological conditions. Ultimately, the concept of equilibrium temperature provides a useful tool to help understand water temperature responses to changing environmental conditions.

Big Springs Creek

Voluminous groundwater source springs were identified at two locations near the head of Big Springs Creek. The first group of springs was identified along the eastern edge of Big Springs Lake. The second group of springs, identified as the North and East Alcove springs, were located approximately 1 km downstream (Figure 2). Together, these source springs provided more than 90% of the streamflow to Big Springs Creek during July and August 2008 (Jeffres *et al*., 2009). Temperature of groundwater emanating from these springs was nearly constant, with average temperatures of 11.7 °C and diurnal variation rarely exceeding 0.1 °C (Figure 5). Springs along the eastern edge of Big Springs Lake are inundated behind a small dam and used for irrigation diversions. Average daily temperature (13.5 °C; $\sigma = 1.5$) of water released from Big Springs Lake (BSC 3.71) was warmer than that of discrete source springs (Figure 5), indicating daytime warming during travel through the 0.5-km reservoir (Deas and Limanto, 2012). However, these approximately 0.2 m^3/s releases co-mingled with the large (~1.2 m^3/s) North and East Alcove spring sources of nearly constant temperature (11–12 °C) approximately 0.5 km downstream from the dam (Figure 2). Because of the low flow volumes discharged from Big Springs Lake during the summer, the North and East Alcove springs largely reset temperature conditions at this location in Big Springs Creek to groundwater temperatures (Jeffres *et al*., 2009).

During the summer, source spring temperatures were well below daytime equilibrium temperatures, forcing high rates of daytime heating downstream from the North and East Alcove springs. The highest rates of heating occurred between these springs and BSC 2.51, a 0.45 km stream reach characterized by extraordinarily high (maximum = 237) bankfull width-to-depth ratios (Jeffres *et al*., 2009). Along this reach during July and August 2008, heating rates derived from mean daily temperatures averaged 3.6 °C/km, whereas heating rates derived from daily maximum temperatures averaged 10.7 °C/km. Daytime stream temperatures continued to rise downstream along Big Springs Creek, however at much lower rates coinciding with reduced channel width-to-depth ratios (Jeffres *et al*., 2009). Between BSC 2.51 and BSC 0.19, heating rates derived from mean daily temperatures averaged 1.2 °C/km, whereas heating rates derived from daily maximum temperatures averaged 1.9 °C/km. Afternoon temperatures at the mouth of Big Springs Creek often exceeded 22 °C, with a maximum observed temperature of 25.0 °C. Source spring temperatures were nearly identical to nighttime equilibrium temperatures (Jeffres *et al*., 2009). Consequently, nighttime flows did not appreciably warm during transit through Big Springs Creek. Between the Alcove Springs and BSC 2.51, mean daily minimum temperatures decreased slightly from 11.7 °C to 11.4 °C. Between

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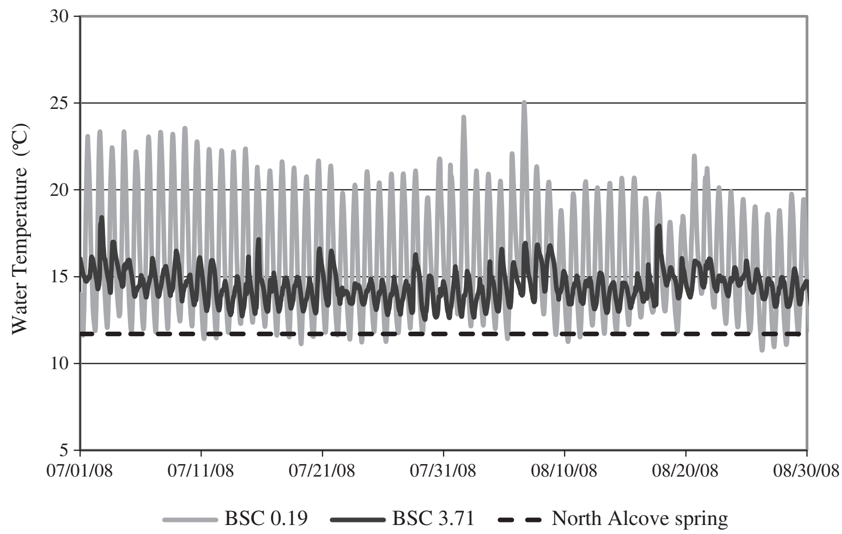

Figure 5. 0.5-h interval stream temperature was measured at the outlet of Big Springs Lake (BSC 3.71) and the mouth of Big Springs Creek (BSC 0.19). The North Alcove spring data logger malfunctioned from July 1 through 11 August 2008. Thus, the average daily temperature of the North Alcove spring from 12 August to 31 August 2008 is presented

BSC 2.51 and BSC 0.19, night time heating rates derived from daily minimum temperatures averaged 0.23 °C/km. Because of short travel times through Big Springs Creek (~6 h), water heated during the daytime was completely replaced the following night by cool source spring flows. This 'replacement water' caused minimum daily stream temperatures at the creek mouth (BSC 0.19) (mean = 12.1 °C; $\sigma = 0.85$) in July and August 2008 to nearly replicate source spring temperatures (Figure 5). This pattern of daytime heating followed by the night time replacement with cool groundwater forced large diurnal temperature variations at the mouth of Big Springs Creek (BSC 0.19) that often exceeded 10 °C. Daily standard deviations of water temperature at BSC 0.19 peaked at 4.1 °C in early July 2008 and showed a gradual decrease in magnitude over the course of the summer due to increased shading from emergent aquatic vegetation. (Figure 6).

Shasta River

Water temperature conditions in the Shasta River immediately downstream from Big Springs Creek reflected the mixing of the two waterways. Because summertime flows in Big Springs Creek were on average five times greater than flows in the Shasta River, water temperature patterns in the

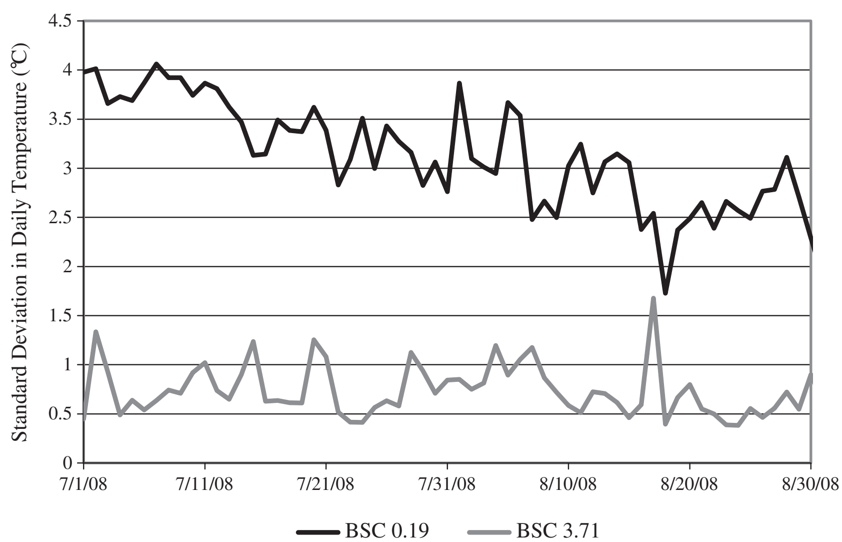

Figure 6. Daily standard deviation in half hourly stream temperature at the outlet of Big Springs Lake (BSC 3.71) and the mouth of Big Springs Creek (BSC 0.19)

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Shasta River approximately 3 km downstream from the confluence of the two waterways (SR 51.68) largely mimicked patterns observed at the mouth of Big Springs Creek (Figure 7). The approximately 3 h transit time of Big Springs Creek water between BSC 0.19 and SR 51.68 explains the observed temporal lag in maximum and minimum temperatures observed at SR 51.68.

The timing of maximum and minimum stream temperatures at locations along the Shasta River downstream from Big Springs Creek was out of phase with meteorological conditions. Typically, maximum temperatures in rivers occur at sunset, whereas minimum temperatures occur at sunrise (Caissie, 2006). However, at monitoring locations between SR 52.64 and SR 44.03, maximum temperatures occurred throughout the night and into the following morning, whereas minimum temperatures occurred throughout the day and into the following night (Figure 7). The timing of maximum and minimum temperatures at any given location along this reach of the Shasta River generally corresponded with the timing of maximum or minimum temperatures at the mouth of Big Springs Creek plus the travel time to the specific downstream Shasta River monitoring location. For example, in July 2008, maximum and minimum temperatures 4 h of travel downstream at SR 51.68 typically occurred at 7:30 PM and 9:30 AM, respectively. Roughly 8 h of travel farther downstream, maximum water temperature at SR 47.12 occurred at 3:30 AM, whereas minimum temperatures occurred at roughly 5:30 PM (Figure 7). The timing of maximum and minimum water temperatures remained out of phase with meteorological conditions at SR 30.82, more than 23 km downstream from Big Springs Creek. These downstream patterns indicate the timing of daily maximum and minimum temperatures was controlled by the velocity of water exported from Big Springs Creek, as opposed to meteorological conditions or channel geometry.

Similar to downstream patterns in the timing of maximum and minimum temperatures, the magnitude of these maximum and minimum temperatures created a longitudinal pattern in diurnal temperature variation. As warm water flowed out of Big Springs Creek in the mid- to late-afternoon and was translated downstream through the Shasta River during the following night, maximum water temperature at downstream monitoring locations was progressively reduced as the water cooled following exposure to night time meteorological conditions. Conversely, as cool water flowed from Big Springs Creek into the Shasta River each night and the following morning, minimum water temperatures downstream progressively increased as this cool water was heated throughout the day. Driven by both the downstream reduction of maximum temperatures and increase in minimum temperatures, diurnal variation diminished progressively downstream to a minimum at a location approximately 12–15 h travel time downstream from Big Springs Creek (Figure 8). In July and August 2008, this location was identified at SR 47.12, approximately 8 km downstream from the mouth of Big Springs Creek (Figure 8). Downstream from SR 47.12, diurnal variation began to increase as (i) initially warm water that cooled during downstream transit from Big Springs Creek the previous night began to warm during the next day; and (ii) initially, cool water from Big Springs Creek that warmed in transit the previous day began to cool during the next night. Interestingly, average diurnal variation at SR 30.82, approximately 24 h (and 16.3 km) of travel downstream from SR 47.12 and 36 h downstream from BSC 0.19 was only 1.79 °C (Figure 8). This suggests the temperature of water exported from Big

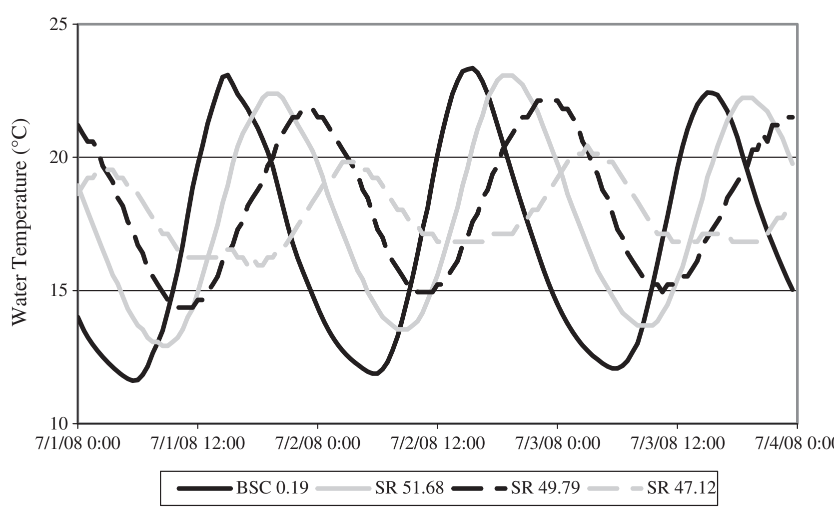

Figure 7. Downstream differences in diurnal stream temperature variation in Big Springs Creek (BSC) and the Shasta River (SR) over four consecutive days in July 2008. Minimum daily temperature variation was observed at Logger SR 47.12, beyond which daily stream temperature variation increased

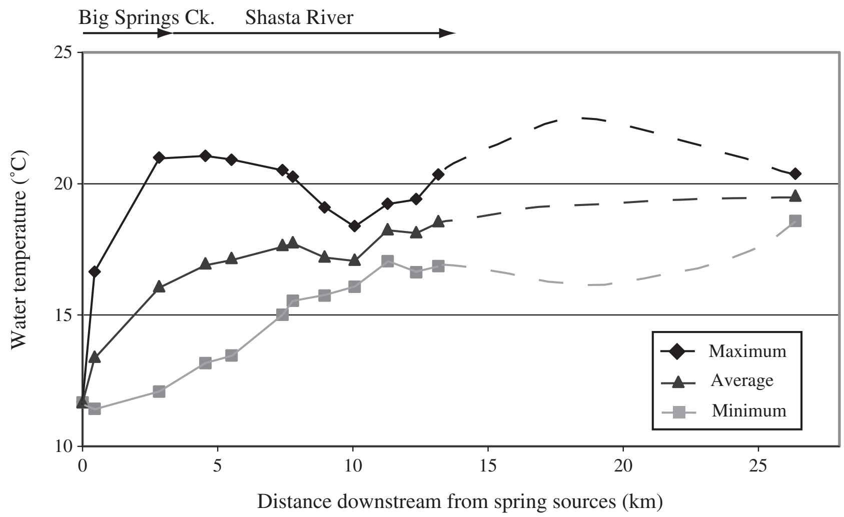

Figure 8. Longitudinal plots of water temperatures measured at monitoring locations located between the North Alcove spring in Big Springs Creek and Logger SR 30.82 in the Shasta River. Data points represent numerical means from the period of July through August 2008, calculated from daily maximum, average and minimum temperatures measured at each monitoring location. Dashed lines represent inferred temperature trends between Loggers SR 44.03 and SR 30.82

Springs Creek was controlling diurnal temperature variation approximately a day and half later in the Shasta River at a distance of more than 23 km downstream.

DISCUSSION AND CONCLUSIONS

Understanding the influence of large groundwater sources on summertime stream temperatures is of emerging importance to water supply and cold-water fisheries management, particularly in volcanic regions throughout the western USA. During low-flow periods in streams with snowmelt and rainfall runoff hydrologic regimes, the temperature of large groundwater and spring-fed tributary sources can control temperature patterns over large downstream distances (Tague *et al*., 2007). Our analyses indicate that for the Shasta River, spatial patterns in the timing and variability of summertime water temperature were dependent on the downstream translation of water exported from the spring-fed tributary Big Springs Creek. The findings of this study suggest that the thermal behaviour of water in spring-fed tributaries can impart unique temperature patterns on downstream waterways, and that these patterns should be considered when managing cold-water fisheries.

Downstream from water sources of constant temperature (e.g. water supply reservoirs, groundwater springs, etc.), patterns in diurnal temperature often develop (Lowney, 2000). Solutions to models presented by Polehn and Kinsel (1997) and Lowney (2000) indicate that under idealized conditions defined by unchanging channel morphology, shading conditions and hydrology, alternating ‘antinodes’ of maximum daily temperature variation and ‘nodes’ of minimum daily temperature variation will occur downstream at locations roughly 12 h of travel time apart. Polehn and Kinsel (1997) also suggest that the magnitude of maximum diurnal temperature variability will diminish downstream until alterations in channel geometry or external sources of heating override the influence of initially stable source temperatures.

Patterns in diurnal water temperature variation downstream from source springs at the head of Big Springs Creek are analogous, albeit imperfectly, to patterns predicted by the aforementioned models. In our study, an apparent antinode of maximum variability consistently occurred at the mouth of Big Springs Creek (BSC 0.19), roughly 6 h of travel time downstream from the spring sources. This was not a true antinode, as defined by Lowney (2000), because the travel time from spring sources to the confluence with the Shasta River was less than 12 h. An abrupt change in channel geometry from the wide, shallow Big Springs Creek (W:D ranges from 9 to 237) to the relatively narrow and deep Shasta River (W:D ranges from 11 to 29) (see Figures 3 and 4) generated this antinode by forcing different heating rates in the two channel reaches. The impact of this channel geometry change can be readily assessed using a simplified form of the advection–diffusion equation

$$\frac{\partial T_w}{\partial t} = -v\frac{\partial T_w}{\partial x} + d\frac{\partial {T_w}^2}{\partial x^2} + \frac{H_n w}{C_p \rho A}$$

where T_w is water temperature (°C), t is the time (seconds), v is the mean channel velocity (m/s), x is the longitudinal distance (m), d is the dispersion coefficient in the downstream direction (m^2/s), w is the channel width (m), H_n is the net

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heat flux across the water surface (W/m^2), C_p is the specific heat of water (4185 J/kg/°C), ρ is the water density (1000 kg/m^3) and A is the cross-sectional area (m^2) (Martin and McCutcheon, 1999). Neglecting diffusion, which for longitudinal gradients are typically small in streams without point inflows, and writing the equation in terms of a parcel being advected downstream at mean channel velocity, v, the equation reduces to

$$\frac{\partial T_w}{\partial t} = \frac{H_n w}{C_p \rho A}$$

Assuming an approximately rectangular channel, the channel width divided by cross-sectional area (on the right-hand side of the equation) reduces to (1/d), where d is depth (m), or

$$\frac{\partial T_w}{\partial t} = \frac{H_n}{C_p \rho d}$$

Mean depths in the Shasta River range from two to eight times mean depths in Big Springs Creek. Thus, for a given set of meteorological conditions at a steady flow rate, the rate of heat change (i.e. $\frac{\partial T_w}{\partial t}$) in the Shasta River as compared with Big Spring Creek is reduced by two to eight times. This effect truncates the range of temperatures downstream of the confluence between Big Springs Creek and the Shasta River.

The effect of truncating the range of water temperatures through changes in channel geometry is particularly evident in the trace maximum daily temperatures (Figure 9) in the Shasta River below Big Springs Creek. When Big Springs Creek waters enter the Shasta River (Location A), note how there is no appreciable additional heating—the maximum does not increase in the downstream direction. If the geometry of the Shasta River were similar to Big Springs Creek, the river would continue to heat in the downstream direction, reaching a maximum approximately 12 h downstream from the spring sources (Location B). A hypothetical maximum temperature trace of this latter condition is shown in Figure 9. Using this hypothetical scenario, the first 'true' node of minimum diurnal variation would then be located 24 h downstream from the spring sources. However, field water temperature and stream velocity data identify the first temperature node at roughly 12 h of travel time (and 8 km) downstream from the first antinode located at the mouth of Big Springs Creek. Subsequent antinodes and nodes are identified roughly 12 h of travel time apart along the Shasta River up to 23 km downstream from Big Springs Creek. The presence of a node at SR 30.82 provides a minimum downstream extent of the influence of source spring temperatures on patterns of diurnal variation in the Shasta River. The distance of temperature influence from constant temperature groundwater is in general agreement with observations from other spring-fed creeks (Webb and Zhang, 1999).

Although downstream patterns in temperature variation were largely predictable, the magnitude of temperature variability, and particularly variability at the mouth of Big Springs Creek, was unexpectedly high. This had substantial consequences for temperature conditions in downstream reaches. In spring-fed streams, groundwater-derived streamflows generally warm slowly and exhibit small temperature variations, particularly close to spring sources (Webb and Zhang, 1999, Tague *et al*., 2007). However, daytime streamflow immediately downstream from cold springs at the head of Big Springs Creek heated rapidly, producing large diurnal variation atypical of most spring-fed streams. The magnitude of this variation was highlighted by the fact that standard deviations of daily stream temperatures approximately 3.5 km downstream from the source springs during August 2008 were an order of magnitude greater than

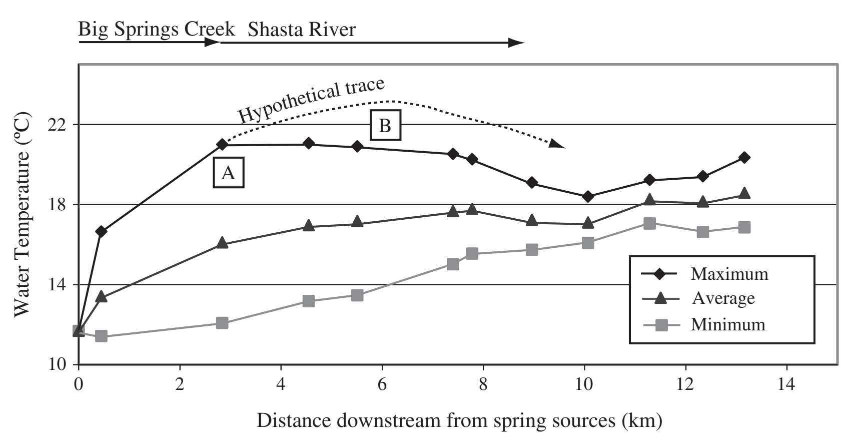

Figure 9. Longitudinal plots of water temperatures measured at monitoring locations located between the North Alcove spring in Big Springs Creek and Logger SR 44.03 in the Shasta River. Dashed line between location 'A' and location 'B' represents the hypothetical trace of maximum temperature if channel geometries in the Shasta River were similar to those observed in Big Springs Creek

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those observed in other spring-fed creeks in the Oregon Cascades over almost identical temporal periods and downstream distances (Tague *et al*., 2007). The observed rates of daytime heating that drove the large diurnal temperature variations were a function of the wide and shallow channel conditions degraded by land use and water management. The elevated daytime temperatures driving this large diurnal variability were translated from Big Springs Creek into the Shasta River each afternoon. The magnitude of these maximum daily temperatures inherited by the Shasta River determined downstream habitat suitability for coho salmon, particularly in reaches immediately downstream from Big Springs Creek, where minimum daily stream temperatures and food resources provided ideal rearing conditions (Nichols *et al*., 2010).

Biotic effects and management implications

Water temperature can be a limiting factor for cold water fish during spring and summer months. The temperature of a stream is a function of diverse thermal inputs, and thus managing water temperature conditions requires an understanding of which thermal inputs play dominant roles in controlling stream temperature both in space and time. As we have shown, downstream temperature patterns in Big Springs Creek and the Shasta River were largely controlled by the fate of constant source temperature spring water. For tens of kilometers downstream from spring sources, the magnitude of maximum stream temperatures were principally controlled by the rate of heating along Big Springs Creek due to daytime solar radiation loading. Alternatively, because warm water in Big Springs Creek was replaced with cold spring water each evening, the magnitude of minimum temperatures over this same distance was driven by the rate of heating along the Shasta River. These downstream patterns in diurnal variation, and both maximum and minimum temperatures, directly affected habitat suitability for coho salmon in channel reaches downstream from the spring sources.

Elevated stream temperature is a primary factor limiting the coho salmon in the Shasta River, particularly during the summer. Rearing juvenile coho typically prefer water temperature near 12–14 °C (Moyle, 2002), whereas optimal growth conditions may occur at slightly higher temperatures up to 17 °C, depending on the availability and quality of food resources (Richter and Kolmes, 2005). The California Department of Fish and Wildlife (Stenhouse *et al*., 2012) suggest 15.5 °C as an upper end of the optimal temperature range for juvenile coho in the Shasta River. In California streams, mean weekly maximum temperature (MWMT), or the 7-day moving average of daily maximum temperatures, has become one of the principal metrics used to characterize thermal tolerance of coho salmon. MWMT of 18 °C is often viewed as an upper thermal threshold (Welsh *et al*., 2001), with temperatures above 18 °C typically forcing coho to search for habitats with cooler water. Although coho salmon are able to rear in streams with maximum temperatures above 18 °C, this is generally only observed where food resource abundance is capable of meeting the increased metabolic demands of elevated temperatures (e.g. Bisson *et al*., 1988), or where cold-water refugia is available, such as groundwater seeps (Bisson *et al*., 1988) and colder tributary confluences (Sutton *et al*., 2007, Sutton and Soto, 2012). An abundance of macro-invertebrate prey, as well as overhead cover and velocity refuge provided by aquatic plants, suggest that coho in Big Springs Creek and the Shasta River near the spring sources can rear at locations where maximum temperatures exceed 18 °C. Although temperature tolerances vary depending on local habitat conditions, coho will generally migrate to more bioenergetically favourable habitats dictated by lower water temperature.

Data from studies conducted concurrently with this work (Chesney *et al*., 2009, Jeffres *et al*., 2009, Nichols *et al*., 2010) suggest that single ‘threshold-based’ (Poole *et al*., 2004) water temperature standards such as MWMT (see NCRWQCB, 2006) may not be an appropriate tool in an aquatic system such as the Shasta River where naturally occurring spatial and temporal variations in water temperatures driven by groundwater inflows are so pronounced. Single temperature threshold-based standards for rearing coho in the Shasta River may be inappropriate for two reasons. First, coho may successfully rear in locations that experience maximum temperatures in excess of an established threshold value (e.g. 18 °C) and also experience prolonged periods where water temperatures reside within an optimal temperature range (e.g. 12–15 °C). Second, coho may unsuccessfully, or choose not to, rear in locations where the threshold temperature value is not exceeded but minimum temperatures never drop into a zone for optimal growth. For example, during the spring of 2008, juvenile coho were observed rearing at the mouth of Big Springs Creek and in the Shasta River more than a kilometer downstream (Chesney *et al*., 2009, Jeffres *et al*., 2009). Maximum temperatures at these locations routinely exceeded 20 °C, but minimum temperatures dropped from 11 °C to 12 °C each night. Not until daily maximum temperatures at these location exceeded 23–24 °C were juvenile coho forced to migrate to more thermally viable habitat, generally located closer to upstream springs (Chesney *et al*., 2009). During July and August 2008, consistently elevated MWMT ($>$ 22 °C) made rearing in these locations generally unsuitable, even though average daily minimum temperature largely matched source spring temperatures. During this summer period, juvenile coho were observed to successfully rear in only three locations throughout the Shasta River Basin—all of which were associated with nearby cold springs (Chesney *et al*., 2009). Although each of these three

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locations exhibited widely varying MWMT magnitudes (14.6–22.5 °C), they were all characterized by daily minimum temperatures (ranging from 13.2 °C to 13.4 °C) that remained close to groundwater spring temperatures. These data suggest that in locations where physical habitat conditions are appropriate and food resources are abundant, juvenile coho can rear in locations where maximum temperatures exceed generally established threshold values but where minimum temperatures provide optimal rearing temperatures for much of each day. Locations of minimal diurnal variation (or 'nodes') (Lowney, 2000) present an entirely different scenario. During the summer of 2008, the first temperature variability node in the Shasta River downstream from Big Springs Creek exhibited reduced MWMT magnitudes (average MWMT < 19 °C in July and August 2008); however, no coho were observed rearing in these locations. Given abundantly available food resources and suitable physical habitat conditions, it is hypothesized that elevated minimum temperatures at these nodes (> 16 °C) limited the ability of coho to metabolize abundantly available food resources.

Ultimately, existing data suggest that juvenile coho utilize reaches of the Shasta River and Big Springs Creek if cover and food resources are available, and instantaneous maximum temperatures do not enter the range of 22–24 °C (Chesney *et al*., 2009). When such instantaneous temperatures are reached, coho migrate towards available cold-water springs or locations where elevated daily maximum temperatures are offset by prolonged daily periods where water temperatures are close to spring temperatures. In 2008, coho salmon remained at both types of locations through the fall until winter when they redistributed throughout the watershed (Chesney *et al*., 2009, Jeffres *et al*., 2009).

Thermal patterns of daily maximum, minimum and mean temperatures observed in Big Springs Creek and the Shasta River clearly complicate the development of water temperature standards that maintain conditions necessary for the successful rearing of juvenile coho. The large spatial and temporal variations in water temperature throughout Big Springs Creek and downstream reaches of the Shasta River can result in locations only kilometers apart where temperature conditions are alternatively beneficial and detrimental. Such inherent spatial and short-term temporal variability of water temperature conditions suggests that single threshold-based standards for water quality may not be sufficient for protecting juvenile coho habitat in the Shasta River Basin or cold-water fishes in other hydrologic basins with large groundwater spring contributions to streamflow. In such basins, 'regime-based' water temperature standards (sensu Poole *et al*., 2004) may be more appropriate. Regime standards are spatially and/or temporally dynamic conditions that incorporate the natural spatial and temporal distribution of forcing factors that influence aquatic ecosystem parameters such as stream temperature. Using the Big Springs Creek and the Shasta River as an example, a regime-based approach might establish multiple upper thresholds for temperature based on daily minimum temperatures. In locations close to spring sources where minimum daily temperatures approximate groundwater temperatures, maximum temperature standards might be elevated. Alternatively, maximum temperature standards could be established at a lower level where daily minimum temperatures are slightly elevated. Further, establishing maximum water temperature standards at locations of temperature nodes may be inappropriate. Such dynamic standards would incorporate the natural patterns of stream temperature downstream from large spring sources to maintain an appropriate distribution of habitat conditions in space and time.

Ultimately, the large and cold groundwater-derived spring flows in Big Springs Creek can provide optimal thermal conditions for rearing coho throughout the summer. Extending the downstream distance of this cold water inherited from the groundwater source springs would dramatically increase the longitudinal extent of thermally viable habitat. Because daily minimum water temperatures typically approach local groundwater temperatures, management efforts aimed at limiting the rate of daytime heating and maximising the downstream distance cold spring flow travels before being heated should be prioritized. In Big Springs Creek, such efforts should principally focus on restoration efforts, including (i) buffering thermal radiation loads through increased shading from emergent and riparian vegetation; and (ii) decreased water transit time through channelisation by emergent aquatic plants. Ongoing studies are currently investigating the effects of such restoration actions. If future data prove that such actions are insufficient to achieve the aforementioned restoration objectives, other restoration activities within Big Springs Creek, including channel alterations, may be needed.

From a broader perspective, spring-fed rivers are a primary source of cold, late summer streamflow in volcanic regions in the western US (Tague *et al*., 2007). With climate warming projected to reduce water volumes in streams sourced predominantly by snowpack, spring-fed rivers will likely provide a greater percentage of total streamflow in these regions during the critical summer months, making habitat conservation strategies focusing on the protection of these unique cold-water resources pertinent. Findings from this study suggest that large, constant temperature spring sources and spring-fed rivers (much like constant temperature releases from water storage reservoirs) can impart unique stream temperature patterns on downstream river reaches that can determine reach-scale habitat suitability for cold-water fishes largely independent from available food resources, protective cover or other habitat suitability metrics. Understanding the spatial extent of stream

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temperature patterns through detailed baseline data collection is a critical step in managing temperature conditions in these unique hydrologic systems. Successful restoration strategies in such hydrologic systems must focus first on limiting the rate of heating immediately downstream from large spring sources and then prioritising restoration actions in locations where daily temperature patterns will allow rearing of cold-water fishes. Ultimately, an understanding of the predictable water temperature patterns downstream from large spring sources can provide numerous opportunities to adaptively manage water temperature conditions through spatially and temporally focused flow and/or habitat restoration actions.

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