Seasonal aquatic macrophytes reduce water temperatures via a riverine canopy in a spring-fed stream

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Abstract: Maximum water temperatures in streams throughout the western USA typically occur in late summer and early autumn, coinciding with low stream flow. However, in the spring-fed Big Springs Creek in northern California, where constant-temperature groundwater springs provide relatively stable stream flow throughout the year, peak water temperatures and maximum diurnal variability occur in spring. We attribute this anomaly to the riverine canopy provided by emergent aquatic macrophytes (e.g., *Polygonum hydropiperoides* and *Nasturtium officinale*), which mimics the shade function of a riparian canopy. Macrophyte biomass increased 264% between January and August 2011. This increase coincided with a 111% reduction in flow velocity and a 53% increase in stream depth. Solar radiation was reduced by an average of 88% in patches of macrophytes that covered ~50% of the water surface during the summer. Decreased solar radiation reduced rates of stream heating, maximum temperatures, and temperature variability. We tested the riverine canopy hypothesis analytically based on a 2-dimensional hydrodynamic and water-temperature model. The model predicted that emergent aquatic macrophytes reduce maximum water temperatures by an average of 5.1°C (p < 0.001) during late summer, when water temperatures in northern California streams typically increase. Our study shows the influence of a riverine canopy on naturally occurring temporal patterns of water temperature in a spring-fed stream. Our results could inform basin-scale management or regulatory strategies to address water-temperature conditions.

Key words: riverine canopy, water temperature, aquatic macrophyte, spring-fed, model, conservation, management

Water temperature is a principal determinant of habitat suitability for juvenile salmonids and other organisms in lotic ecosystems (Bjornn and Reiser 1991, Caissie 2006). Elevated water temperatures have been linked to increased stress and mortality of juvenile salmonids that rear in freshwater lotic habitats throughout the summer months (Marine and Cech 2004, de Brabandere et al. 2007). Therefore, many management and recovery efforts for threatened or endangered salmonids have been focused on reducing elevated summer water temperatures (Poole et al. 2004, Richter and Kolmes 2005). Regulatory personnel commonly use water-temperature metrics (e.g., 7-d running average of daily maximum temperatures) to assess macrohabitat quality during all freshwater salmonid life stages (USEPA 2003). However, threshold-based water-temperature targets often do not include complex spatial and temporal watertemperature dynamics that have important implications for regulatory compliance strategies or mitigating factors, such as food availability, that have direct effects on the thermal tolerance thresholds of coldwater fish (Poole et al. 2004).

Stream temperatures are expected to rise throughout western North America in response to warming under climate change (Null et al. 2013). Coldwater fishes are anticipated to respond to such warming trends by altering lifehistory strategies, such as contracting their ranges by moving to higher-elevation reaches with cooler water temperatures when migratory pathways are present (Isaak and Rieman 2013, Eby et al. 2014). However, spring-fed streams may provide a unique hedge to this anticipated range contraction. Under most climate-change scenarios, groundwater inflows to spring-fed streams are anticipated to remain generally stable and cool, albeit with reduced volumes (Tague et al. 2008).

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Thus, spring-fed streams that are accessible to salmonids may be ideal targets for conservation efforts focused on salmon recovery.

Spring-fed streams can exhibit water-temperature patterns that are temporally and spatially unique. During the summer, spring-fed streams in the western Oregon Cascades were cooler, exhibited less temperature variability, and were less sensitive to variations in air temperature than streams with water sourced from runoff and shallow subsurface flow (Tague et al. 2007). Unique spatial patterns of thermal nodes and antinodes occur near the source of thermally stable groundwater inputs to a northern California spring-fed stream (Nichols et al. 2014). Such observations suggest that features of spring-fed streams, such as stable base flow and constant-temperature water sources, are important to understanding how water temperatures in such streams may respond to climate change or river-restoration activities.

Observations from Big Springs Creek, a spring-fed stream in northern California, suggest that seasonal growth patterns of aquatic macrophytes may be an important, but often overlooked component of water-temperature dynamics. The seasonal growth of emergent aquatic macrophytes in rivers influences habitat conditions in myriad ways. Interactions between macrophytes and stream flow influence channel hydraulics (Green 2005b, Bal et al. 2011, O'Hare et al. 2011), sediment transport and depositional processes (Madsen et al. 2001, Gurnell et al. 2010, O'Hare et al. 2011), nutrient dynamics (de Brabandere et al. 2007), and water quality (Madsen and Cedergreen 2002, Wilcock et al. 2004).

However, these interactions also could influence water temperatures. The relationships among stream temperature, channel hydraulics, and riparian canopy are wellestablished (Poole and Berman 2001, Caissie 2006, Webb et al. 2008). Channel hydraulics influence stream temperatures by changing heating capacity, either via changes to the volume of water (i.e., inflows and outflows), streambed heat exchanges, or narrowing and deepening by altered channel forms (Caissie 2006, Webb et al. 2008). Riparian vegetation is credited primarily with reducing thermal loading to stream channels by blocking solar radiation from the water surface (Poole and Berman 2001, Caissie 2006, Webb et al. 2008). However, riparian canopies are less effective moderators of stream temperature in wider stream channels because the canopies block a smaller portion of the channel (Poole and Berman 2001).

Where riparian canopies are absent or ineffective, riverine canopies created by aquatic macrophytes may offer an important, analogous function. Aquatic macrophytes are quintessential 'ecosystem engineers' (Jones et al. 1994, O'Hare et al. 2012), and are particularly influential in lowland, spring-fed streams with largely stable flow regimes sourced from large groundwater springs (Champion and Tanner 2000). However, despite the important roles of channel hydraulics and shading in regulating spring-fed stream temperatures (Whitledge et al. 2006), the effects of seasonal emergent macrophyte growth on water-temperature patterns have not been widely studied. Microthermal gradients were observed in patches of aquatic macrophytes in Dorset rivers (UK), but these variations were limited to patches that covered a few cm to m of stream channel (Clark et al. 1999) and the authors did not explore system-scale aquatic macrophyte communities and their potential effects on water temperature. System-scale studies across a range of stream sizes in Australia and Austria show that patchy shade plays a significant role in moderating maximum water temperatures (Rutherford et al. 2004, Kalny et al. 2017), but these studies were limited to riparian, not riverine, canopies.

We used a combination of empirical and analytic assessments to explore relationships among the seasonal growth of aquatic macrophytes in Big Springs Creek, hydraulic conditions, and water-temperature patterns. Our objective was to identify the critical factors that influenced water temperature to help inform on-going conservation activities in Big Springs Creek and the downstream Shasta River. We used empirical data to quantify relationships among aquatic macrophytes, channel hydraulics, reduction in solar radiation by macrophyte shading, and water temperature. Our hypothesis was that seasonal aquatic macrophyte growth moderated maximum water temperatures during a period when they typically reach their annual peak by creating a riverine canopy. We developed a 2-dimensional (2-D) hydrodynamic and water-temperature model to test the dynamics observed in field data over a more extensive spatial and temporal domain. Investigators have used theoretical and empirical models to examine the influence of aquatic macrophytes on flow conditions (Champion and Tanner 2000, Green 2005a, Gurnell 2014) and water quality (Cox 2003, Srivastava et al. 2008), but we are not aware of studies in which investigators quantified the system-scale influence of aquatic macrophytes on water temperature. Our goal was to quantify the relationship between emergent aquatic macrophytes and water temperature and to improve understanding of potentially effective approaches to managing elevated water temperatures in spring-fed streams. Our results can be applied broadly to streams that support extensive aquatic macrophyte growth and may be considered for conservation actions or water-resource management based on water-temperature metrics.

Background

Big Springs Creek is a 3.7-km-long tributary to the Shasta River in Siskiyou County, California (USA; Fig. 1). It is characterized by relatively large volumes (~2.3 m³/s) of cool (10–12°C) spring-fed discharge (Nichols et al. 2014). Rainfall and snowmelt contributions are negligible. Modest surface-water diversions (<0.3 m³/s) and regional groundwater extraction occur between 1 April and 1 Octo-



Figure 1. Map of the study area and monitoring sites.

ber (Null et al. 2010, Nichols et al. 2014). The creek is entirely contained on 2 private properties, both of which support cattle-ranching activities, and has been the focus of restoration efforts because of its robust potential to support coldwater fishes in the creek and downstream in the Shasta River for tens of km (Jeffres et al. 2009, Null et al. 2010, Nichols et al. 2014). These efforts have been focused on reducing elevated water temperatures during spring and summer.

Historical landuse practices included unrestricted cattle grazing in the stream channel. Previous investigators have illustrated the relationship between livestock grazing and elevated water temperatures (Belsky et al. 1999, Agouridis et al. 2005), primarily via removal of riparian vegetation. Prior to restoration actions in Big Springs Creek, maximum daily water temperatures peaked $>25^{\circ}$ C (Jeffres et al. 2009, Nichols et al. 2014). Since restoration activities were initiated in 2009 to exclude cattle from the stream channel, annual maximum stream temperatures have declined as much as 4°C (Willis and Deas 2012), and generally remain within optimal growth ranges for juvenile rearing salmon and trout (USEPA 2003). The stream supports an array of anadromous salmonids, including Coho Salmon (*Oncorhynchus kisutch*, a federally threatened species), autumn-run Chi-

nook Salmon (*Oncorhynchus tshawytscha*), and Steelhead Trout (*Oncorhynchus mykiss*) (Willis et al. 2012).

Before the start of restoration activities on Big Springs Creek, a monitoring program was designed and implemented to track the response of a broad array of physical, chemical, and biological variables (Jeffres et al. 2009). The objective of the monitoring program was to characterize baseline conditions of each variable, support long-term monitoring to track each variable's response to conservation actions, and identify areas where targeted, short-term experiments could improve understanding of key processes in the stream. The monitoring program also was designed to support the development of a 2-D, depth-averaged hydrodynamic and water-temperature model to test a range of potential conservation activities across an extensive spatial and temporal domain. Solar radiation loads are a principal component of the heat budget because of limited woody riparian vegetation and high width : depth ratios throughout Big Springs Creek (Nichols et al. 2014). The model was developed in 2 dimensions to capture spatial, volumetric, and thermal variability of groundwater spring inflow sources and to enable simulations of potential conservation activities that could alter channel forms substantially to reduce incoming radiation (Jeffres et al. 2009). Analysis of data collected in 2011 suggested that the seasonal growth of aquatic macrophytes moderated water-temperature dynamics (Willis et al. 2012) and provided the basis for our study.

METHODS

Aquatic macrophyte biomass

Aquatic macrophytes were harvested from 6 randomly selected sampling locations along a 100-m stream reach extending downstream from Big Springs Creek site 9 at river km 0.19 (Fig. 1) on each of 4 sampling dates in 2011: 20 January, 29 March, 24 May, and 22 August. Previous transect surveys of % cover and aquatic macrophyte species provided by The Nature Conservancy (unpublished data) and systematic photographic documentation of aquatic macrophyte growth conditions throughout Big Springs Creek since 2009 suggested that site 9 was representative of average macrophyte conditions in the creek. Visual evidence of previous harvests prevented the duplication of sampling locations. At each sampling location, all above-streambed biomass rooted within a 0.37-m² polyvinyl chloride (PVC)-frame quadrat was harvested. Samples were agitated in the stream to reduce the presence of clinging macroinvertebrates and other detrital material, then placed in individually labeled bags and returned to the laboratory. In the laboratory, plants were dried at 65°C for \geq 72 h and weighed. Samples were then combusted in a muffle furnace for 4 h at 475°C, cooled, and reweighed to derive ash-free dry mass (AFDM). Mean standing macrophyte stock from each sampling date was reported as g AFDM/m². Cohen's d was used to explore the effect size between periods of mimimum and maximum biomass. It was calculated by subtracting the means of macrophyte biomass samples collected in January and August 2011, and dividing that value by the pooled standard deviations of the samples (Cohen 1988).

Macrophyte shading and % cover

Shading effects associated with aquatic macrophytes were quantified based on measurements of solar radiation made with a solar pyranometer (CMP 3, directional error < 20 W/m^2 ; Kipp and Zonen, Delft, The Netherlands). Hourly measurements were taken between 1000 and 1600 h at the water surface at 2 locations along Big Springs Creek on 20 July and 23 August 2011 (Fig. 1). Each location was selected to assess a cover type that was typical throughout the stream: open water or emergent aquatic macrophytes. For each cover type, solar radiation values were reported for each sampling event as was % solar radiation reduction relative to solar radiation measured over open water.

Percent cover was quantified based on a combination of surveys and photographs to estimate the areal extent of emergent macrophytes during periods of maximum biomass. Where access permitted, surveys were conducted at 18 cross sections distributed throughout Big Springs Creek on 7 September 2011. At 2-m increments across each channel cross section, a 1-m² quadrat was surveyed visually for species present and macrophyte cover (aquatic macrophytes that emerged above the water surface) to the nearest 10%. Data for all sampling points were averaged to calculate % cover for each cross section. Calculated % cover was compared to visual estimates based on photographs of each site to establish a consistent approach for locations where surveys were not permitted. Up- and downstream photographs were taken from the middle of the stream channel to provide images of transects. These transect images were used to make visual estimates of macrophyte cover as per field surveys. Monthly photographs were taken at all locations to monitor the progression of emergent growth (i.e., growth above the water surface) from 1 April through 30 September 2011.

Channel hydraulics

Flow velocity measurements were made systematically across a single channel cross section 20 m upstream from the biomass sampling location (site 9; Fig. 1). Measurements typically were completed during aquatic macrophyte sampling and occurred on 19 January, 23 March, 2 June, and 23 August 2011. Beginning at the stream margin, velocity sampling locations were identified at 1.0-m horizontal increments. At each sampling location, 6 vertical velocity measurements were collected: immediately above the stream bed and below the water surface, and at intermediate depth increments of 80, 60, 40, and 20% of total measured water depth. Velocities were measured using a Flowmate 2000 (Marsh-McBirney, Frederick, Maryland), which has an accuracy of $\pm 2\%$ of the total velocity measurement and ± 0.02 m/s at 0 flow. Two-D velocity profiles were created in ArcMap (version 10; Environmental Systems Research Institute, Redlands, California) using inverse distance weighted (IDW) interpolations. Mean cross-section velocities for each sampling date were calculated by dividing mean daily discharge (obtained from an upstream gage) by cross-sectional area. The quotient of cross-sectional area and wetted width was used to represent mean channel depth. Manning's n was calculated for the cross section during each sampling event as:

$$n = \frac{\sqrt[3]{R} \cdot \sqrt{S}}{\nu},$$
 (Eq. 1)

where *R* is hydraulic radius (m), *S* is bed slope (derived from channel long profile survey) (m/m), and ν is mean cross-section velocity (m/s).

Manning's *n* was calculated for vegetated and unvegetated portions of the channel because of the spatial variability of aquatic macrophytes in the sampled cross section. The hydraulic radius for each vegetated or unvegetated portion of the cross section was calculated as:

$$R = \frac{A}{2d + w},$$
 (Eq. 2)

where *A* is area of vegetated or unvegetated portion of the channel (m^2) , *d* is mean water depth (m), and *w* is width of vegetated or unvegetated portion of the channel (m).

Mean flow velocities were calculated from point-velocity measurements collected in the vegetated or unvegetated portions of the cross section, whereas bed slope values were unchanged from those used in the total cross-section Manning's *n* calculation. Vegetated and unvegetated values were applied in the hydrodynamic model to represent lateral and longitudinal variable roughness in areas of aquatic macrophytes or open channel, respectively.

Hydrology

Stream flow in Big Springs Creek was quantified using standard discharge measurement and computational methods (Rantz 1982). A stream gage was established at site 4 (Fig. 1), which was upstream of a grade-control structure and minimized the effects of aquatic macrophytes on stage. Access to discharge-monitoring cross sections was limited to monthly sampling events. Monthly measured discharges and continuous river stage data collected with a Global Water WL-16 submersible pressure transducer (Global Water, College Station, Texas) were used to quantify a stagedischarge relationship based on a power function. This relationship was used subsequently with continuous river stage data to develop a continuous (10-min interval) streamflow time series for Big Springs Creek. We used the hydrologic data to quantify hydraulic parameters and to define boundary conditions in the hydrodynamic model.

Channel geometry

Big Springs Creek channel morphology was characterized based on topographic survey data collected in 2008. We used these data to develop the 2-D hydrodynamic and water-temperature model. Local field topographic surveys were completed using a TOPCON HiPer Lite+ Real-Time Kinematic Global Positioning System survey unit (Topcon Positioning Systems, Inc., Livermore, California), which has a horizontal and vertical accuracy of <2 cm. Longitudinal profiles of the channel bed and water surface were conducted along the channel thalweg while wading. In addition, 64 channel cross sections were surveyed across straight reaches and at meander bend apexes throughout Big Springs Creek. Each cross-section survey contained ≥ 13 points, with survey-point densities greater at locations with higher topographic variability. Cross-section surveys repeated at selected monitoring locations in 2011 identified only minor changes in bed topography, indicating that the more comprehensive 2008 cross-section survey data adequately represented topographic conditions throughout Big Springs Creek in 2011.

Meteorology

Meteorological conditions were monitored at 30-min intervals at a meteorological station near site 7 (Fig. 1). Air

temperature, relative humidity, precipitation, wind speed, wind direction, and solar radiation were monitored with a Campbell Scientific WXT520 weather station (Campbell Scientific, Inc., Logan, Utah). We used these data to implement the water-temperature model.

Water temperature

Water temperature was monitored at 5 springs and 10 stream locations throughout Big Springs Creek (Fig. 1) for the period 1 April–30 September 2011 with HOBO[®] Pro v2 water-temperature data loggers (Onset Computer Corporation, Bourne, Massachusetts). The data loggers have an accuracy of $\pm 0.2^{\circ}$ C over the range from -40 to 50°C and recorded at 30-min sampling intervals. We used these data to implement and calibrate the water-temperature model.

2-D hydrodynamic and water-temperature model application

We generated a 2-D, depth-averaged, finite-element hydrodynamic and water-temperature numerical model of Big Springs Creek with the aid of the RMA suite of finiteelement modeling software (RMA-2, version 8.1b; RMA-11, version 8.7f; Resource Modeling Associates, Sydney, Australia). We simulated hourly flow and water-temperature conditions for the period 1 April through 30 September 2011. We used cross-sectional topographic data to generate a bathymetric map of the creek with Surfer (version 8; Golden Software, Golden, Colorado). A finite element mesh was generated using RMAGEN, from which we simulated flow (RMA-2) and water-temperature (RMA-11) conditions at hourly time steps. We applied hourly flow and watertemperature boundary conditions at all inflows (dam release and springs) and used hourly meteorological data. We represented aquatic macrophytes in model elements (Fig. 2) based on a roughness coefficient (Manning's n) and shading (solar radiation reduction) factor. We used data from the macrophyte cover surveys and photographic images to define the distribution of aquatic macrophytes in the model and to determine which elements represented macrophytes that were submerged below or emerged above the water surface. Only elements representing macrophytes that emerged above the water surface were assigned an average solar radiation reduction factor based on the shade monitoring results (88% solar radiation reduction). To simplify the computational process, we used the average shade calculated from all measurements and assumed that elements representing submerged macrophytes have negligible shading effects. We assigned elements devoid of aquatic macrophytes a roughness coefficient associated with an open channel (i.e., nonvegetated) estimated from the channel hydraulics monitoring. For model elements representing mixed-substrate open channel, Manning's n = 0.07; for macrophytes, Manning's n = 0.31. Other substrates present included bedrock, tules, and willows, with Manning's



Figure 2. A graphical representation of the model mesh. Each element is assigned a roughness and shade factor to represent shaded or open channel. Bold numbers show roughness values for each element type.

n = 0.02, 0.31, and 0.02, respectively. We assigned a rock berm in one portion of the model domain a value of 0.5.

We simulated 3 configurations to assess the relationship between aquatic macrophyte growth and water temperature (Table 1): no aquatic macrophytes, submerged aquatic macrophytes, and seasonal emergent aquatic macrophyte growth (i.e., representative of observed conditions). For each scenario representing aquatic macrophytes, we assigned roughness and shade elements based on observed distribution of aquatic macrophyte growth. We used the monthly photographs taken to monitor the progression of emergent aquatic macrophyte growth to identify the period when seasonal growth shifted from predominantly submerged aquatic macrophytes to emergent aquatic macrophytes. To simplify the computational process, we represented shade as a binary function: no shade was simulated

Table 1. A summary of the 3 configurations simulated using the 2-dimensional hydrodynamic and water-temperature model. n = Manning's roughness coefficient.

Configuration	Roughness elements	Shade elements		
No aquatic macrophytes	Bed material ($n = 0.07$)	Open channel (no shade)		
Submerged aquatic macrophytes	Aquatic macrophytes ($n = 0.31$), bed material ($n = 0.07$)	Open channel (no shade)		
Seasonal emergent aquatic macrophyte growth	Aquatic macrophytes ($n = 0.31$), bed material ($n = 0.07$)	Aquatic macrophytes (88% solar radiation reduction), open channel (no shade)		

from 1 April through 30 June (pre-emergent), and shade was simulated from 1 July through 30 September (post-emergent).

We compared hourly simulation results for 1 April through 30 September (n = 4392) to observed data at 10 locations distributed longitudinally throughout Big Springs Creek, and analyzed the comparisons to assess model performance via statistical metrics and a graphical review of results. Statistical metrics used for calibration included mean bias, mean absolute error (MAE), and root mean square error (RMSE) (Maidment 1993, Null et al. 2010). We used mean bias to identify systematic over- or underprediction by the model (mean bias < 1°C was desirable). We used MAE to segregate different management actions for coldwater fish. A resolution of <1°C was sufficient for those decisions. Management applications were tested in a study subsequent to this preliminary model development and assessment. RMSE was used to identify large deviations from observed conditions (desired model performance was RMSE < 1.5MAE). In selecting these targets, we considered criteria established for other hydrodynamic and water-temperature modeling applications in the Shasta Basin (Null et al. 2010) and other hourly, deterministic water-temperature models (Caissie 2006), including those that met the criteria for regulatory applications (NCRWQCB 2006). In addition, the targets reflected the need for increased accuracy to assess the major physical processes controlling water temperatures on a refined spatial and temporal scale. We plotted simulated results and observed data to examine performance graphically throughout the time series.

Once the major physical processes were identified via calibration, we further analyzed results by comparing the magnitude, timing, and variability of maximum water temperatures for each configuration to the calibrated results. We compared changes in magnitude based on daily maximum water temperatures simulated for each configuration. We statistically analyzed for pairwise differences between means with a Tukey multiple comparison procedure. Significance was declared at $\alpha = 0.05$. We used the timing of the maximum weekly maximum water temperature (MWMT; the annual maximum of the 7-d average of daily maximum temperature [7DADM]) to identify the seasonal shift from increasing to decreasing maximum water temperatures. We analyzed the variability of daily maximum water temperatures based on the standard deviation (SD) of the 7-d moving average.

RESULTS

Aquatic macrophyte growth influences on flow velocity, depths, and shading

During the monitoring period, emergent macrophyte species (e.g., *Polygonum hydropiperoides* and *Nasturtium officinale*) progressively emerged from the water column while submerged species (e.g., *Myriophyllum sibiricum*) occupied the understory (Figs 3A, B, 4A, 5A, B). In general, all identified species were native. Macrophyte biomass was lowest in the winter (mean = 35.5 g AFDM/m²) and highest in the late summer to early autumn (mean = 390.9 g AFDM/m²) (Fig. 4A). This strong, positive seasonal growth pattern was confirmed with a simple exponential regression model ($R^2 = 0.9886$; Fig. 4A) based on sample means and was further supported by a large (1.77) Cohen's *d* value (effect size).

Seasonal aquatic macrophyte growth progressively slowed flow velocities throughout the growing season (Fig. 5A, B). Flow velocities during early spring (March and April) averaged 0.38 m/s, and decreased to a mean of 0.18 m/s in the late summer (August and September). A logarithmic relationship ($-439.6\ln x - 417.27$; $R^2 = 0.8378$) correlating cross-



Figure 3. Seasonal macrophyte growth in Big Springs Creek in (A) May and (B) September 2011.



Figure 4. Mean (\pm SE, n = 6) standing crop of aquatic macrophytes (A) and continuous river stage and discharge (B) measured during the 2011 sampling period. AFDM = ash-free dry mass. Dates are formatted m/dd.

section-averaged velocity and measured macrophyte biomass (n = 4) confirmed the negative relationship between velocity and biomass. River stage (depth) was slightly negatively correlated (Pearson's r = -0.47) with streamflow magnitudes in Big Springs Creek (Fig. 4B). Average crosssectional Manning's n values at the sampling site ranged from 0.08 in March 2011 to 0.21 in August 2011.

We next examined how emergent aquatic macrophytes influenced stream temperature by reducing incoming solar radiation. Emergent macrophytes reduced solar radiation loads in vegetated channel areas by an average of 88% (Table 2). Aquatic macrophytes covered 51% of the water surface in Big Springs Creek, but average % cover for each cross section ranged from 14 to 90%.

2-D hydrodynamic and water-temperature model development and application

We applied the 2-D hydrodynamic and water-temperature model to resolve the spatial and temporal discontinuities of the empirical data and to explore the relationship between water-temperature dynamics and aquatic macrophyte influence on hydraulics and shade. Model simulations that neglected the roughness and shade effects of aquatic macrophytes failed to reproduce observed water-temperature



Figure 5. Flow velocity contour profiles for the Big Springs Creek sampling site, representing periods of seasonal minimum (A) and maximum (B) macrophyte biomass in 2011. Approximate locations of aquatic macrophytes within the water column are illustrated. AFDM = ash-free dry mass.

	Open channel	Aquatic macrophyte		
Date (m/dd/yy) and time (h PST)	SR (W/m ²)	SR (W/m ²)	Shade (%)	
7/20/11 0900	700	35	95	
7/20/11 1000	866	134	85	
7/20/11 1100	970	151	84	
7/20/11 1200	1020	165	84	
7/20/11 1300	991	179	82	
7/20/11 1400	934	180	81	
7/20/11 1500	821	176	79	
8/23/11 0900	605	46	92	
8/23/11 1000	769	45	94	
8/23/11 1100	867	86	90	
8/23/11 1200	919	82	91	
8/23/11 1300	915	22	98	
8/23/11 1400	845	114	87	
8/23/11 1500	684	52	92	
Average shade			88	

Table 2. A summary of solar radiation (SR) measured at the water surface of Big Springs Creek under open (i.e., unimpaired) and aquatic macrophyte (i.e., shaded) areas. PST = Pacific standard time. Dates are formatted m/dd/yy.

timing and magnitudes at multiple sites along the creek within the performance criteria (Table 3). For all simulations and calibration sites, RMSE performance criteria were satisfied (RMSE < 1.5MAE). However, for the 'no aquatic macrophytes' and 'submerged aquatic macrophyte' simulations, mean bias and MAE performance criteria were not met at all sites. Mean bias and MAE criteria were met at sites near boundary conditions (sites 1–3), but performance failed to meet the identified criteria by site 4, and showed

progressively poorer performance at downstream locations. For both simulations, water temperatures were consistently overestimated, with MAE as high as 1.9°C. However, when both shade and roughness attributes of seasonal emergent aquatic macrophyte growth were represented in the model, performance criteria were met at all longitudinal locations.

Graphical examination of model results suggests that MAE in the 'seasonal emergent aquatic macrophyte' configuration had 2 main causes: shifts in phase timing (i.e.,

Table 3. A summary of performance statistics for the Big Springs model for simulations that represent roughness or shade features of seasonal aquatic macrophyte growth and a control simulation that includes neither roughness nor shade features. MAE = mean absolute error, RMSE = root mean square error. All units are °C except river km.

Site	River km	No macrophytes		Submerged macrophytes		Seasonal emergent macrophytes				
		Mean bias	MAE	RMSE	Mean bias	MAE	RMSE	Mean bias	MAE	RMSE
1 ^a	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	3.3	-0.4	0.6	0.7	-0.3	0.6	0.7	-0.8	0.8	1.0
3	3.0	0.6	0.8	1.0	0.6	0.8	1.0	0.3	0.5	0.7
4	2.7	1.0	1.3	1.8	1.1	1.3	1.8	0.5	0.8	1.0
5	2.6	1.0	1.3	1.9	1.1	1.4	1.8	0.4	0.8	1.0
6	2.3	1.0	1.4	1.9	1.0	1.4	1.8	0.3	0.8	0.9
7	1.5	1.1	1.6	2.4	1.3	1.7	2.2	0.3	0.8	1.0
8	0.8	1.2	1.8	2.7	1.3	1.8	2.4	0.2	0.9	1.1
9	0.4	0.8	1.7	2.5	0.9	1.5	2.0	0.2	0.8	1.1
10	0.0	0.7	1.9	2.7	0.9	1.5	2.0	0.1	0.9	1.1

^a Boundary condition



- Observed - Seasonal emergent aquatic macrophytes

Figure 6. Observed and simulated water temperatures at site 10, near the mouth of Big Springs Creek.

the timing of daily maximum and minimum water temperatures) and poorer performance during April and May. We examined observed data and simulated results at the mouth of the creek (site 10; Fig. 1) to assess the cumulative effect of the major physical processes that influenced water temperature in Big Springs Creek and to minimize local effects associated with proximity to discrete groundwaterfed spring sources. We explored phase timing by comparing the timing of observed daily maximum water temperatures at site 10 (Fig. 1) with simulated daily maxima. The 'seasonal emergent aquatic macrophyte' configuration generally shifted the timing of simulated daily maximum temperatures later by an average of 0.7 h over the simulation period (Fig. 6)—a difference of <1 time step. Phase timing differed more often during the 1 April through 30 June simulation period, prior to the simulated onset of seasonal shading by emergent aquatic macrophytes. Relatively poorer performance during this period suggests that a more refined representation of seasonal aquatic macrophyte growth (e.g., monthly) may be desirable.

Once an analysis of the model simulations confirmed that hydraulic and shade features of emergent aquatic macrophytes play an important role regulating seasonal water temperatures, we used additional analyses at site 10 to quantify their relative influence on daily maximum water temperatures. Daily maximum water-temperature results for each configuration were compared for the period 1 July through 30 September 2011, the period during which shade was simulated in the 'seasonal emergent aquatic macrophyte' configuration. The Tukey multiple comparison procedure showed that hydraulics and shade each significantly affected daily maximum water temperatures (p < 0.001). The hydraulic effects of submerged aquatic macrophytes reduced

average daily maximum water temperatures by $1.2^{\circ}C$ (95% confidence interval [CI] = $1.1-1.3^{\circ}C$) (Fig. 7). When shade was applied, average daily maximum water temperatures were an additional $3.9^{\circ}C$ (95% CI = $3.8-3.9^{\circ}C$) cooler. In total, shade and hydraulic effects of seasonal emergent aquatic macrophytes reduced daily maximum water temperatures in Big Springs Creek by an average of $5.1^{\circ}C$.

A review of 7DADM time series for each model configuration suggests that seasonal emergent aquatic macro-



Figure 7. Box-and-whisker plots of the daily maximum water temperatures at site 10 for each aquatic macrophyte configuration comparing discrete effects of hydraulic and shade features of aquatic macrophytes. Lines in boxes are medians, box ends are quartiles, whiskers are 10th and 90th percentiles, and circles show outliers for each configuration's modeled results. Results are for the period 1 July to 30 September 2011.



Figure 8. Seven-day average daily maximum temperatures (7DADM) (A) and standard deviation (SD) for 7DADM (B) for observed data and each configuration's modeled results.

phytes also affect the timing of the seasonal shift from warming to cooling and the variability of the 7DADM. The timing of the seasonal shift from warming to cooling was identified based on the date of the MWMT. In the 'no aquatic macrophytes' and 'submerged aquatic macrophytes' simulations, the MWMT occurred on 29 July 2011 (Fig. 8A). However, the results of the 'seasonal emergent aquatic macrophytes' were substantially different for the timing and magnitude of MWMT. When shade features of emergent aquatic macrophytes were taken into account, MWMT occurred on 21 June 2011, 39 d earlier than the scenarios in which the effects of emergent aquatic macrophytes were neglected. Last, the variance in water temperature was analyzed using the SD of the 7DADM (Fig. 8B). In the 'seasonal emergent aquatic macrophyte' simulation, the SD prior to the onset of shade (i.e., only hydraulic effects of aquatic macrophytes were active) averaged 1.6°C. After shade was applied (i.e., both shade and hydraulic effects were active), the average SD decreased to 0.7°C.

DISCUSSION

Riverine canopy

We investigated whether seasonal aquatic macrophyte growth can reduce seasonal water-temperature trends in a spring-fed stream. Emergent aquatic macrophytes are not typically considered a significant component of a stream's thermal dynamics, but our results illustrate that aquatic macrophytes play an important role in regulating stream temperatures. Specifically, our results support the hypothesis that seasonal aquatic macrophyte growth moderates maximum water temperatures via the shading and hydraulic effects of its riverine canopy.

Field data illustrated how seasonal growth of aquatic macrophytes is a major factor controlling water-temperature conditions in Big Springs Creek. Biomass results and large Cohen's *d* values provided evidence of large, positive changes in aquatic macrophyte biomass throughout the 2011 growth season, resulting in substantial hydraulic and shading effects. Velocity reductions were induced by increased channel roughness associated with macrophyte growth (de Doncker et al. 2009), an observation largely confirmed by a general positive correlation between channel depth (normalized by stream flow) and biomass. The slightly negative correlation between stage and streamflow magnitudes suggest that macrophyte-induced roughness was more dominant than streamflow magnitude in controlling channel depth. This field-based evidence indicates that seasonal increases in biomass and associated macrophyte roughness decreased flow velocities and increased channel depths throughout the macrophyte growing season in Big Springs Creek, whereas flow rates declined during the period of local and regional agricultural water use. As a result, maximum water temperatures showed a notably cooler pattern, with less variability, and a smaller diurnal range after emergence of aquatic macrophytes. In addition, water temperatures began to cool more than a month earlier than would have occurred without the riverine canopy.

Riverine canopies function similarly to riparian canopies, but have important and distinct advantages. Riparian canopies are most effective for narrow channels, but their ability to mitigate elevated water temperatures decreases as channel width increases (Poole and Berman 2001). Because riverine canopies occupy the channel itself, rather than being restricted to the banks, they mitigate solar radiation loading over a larger range of stream sizes. In addition, riverine canopies expand the category of streams that may be managed for water temperature to include those with limited ability to support riparian growth, but high potential for emergent aquatic macrophyte growth. Such streams have been identified in the UK and New Zealand (Clark et al. 1999, Champion and Tanner 2000, Tague et al. 2008, Nichols et al. 2014) as well as in northern California and the Oregon Cascades.

Our study illustrates the relationship between a riverine canopy and water temperature, but additional research is needed to explore the limits of this aquatic macrophytebased process. The patchy distribution of aquatic macrophytes should be explored to estimate the density and distribution necessary for an effective riverine canopy. The 51% average cover provided by the riparian canopy exceeds the minimum coverage recommended for effective shade (Kalny et al. 2017), but the range of cover (14-90%) suggests that some areas may have insufficient macrophyte density to provide effective shade. In studies of patchy riparian shade in Australia and Austria, sudden decreases in vegetation density showed the potential to result in substantial water-temperature changes that are likely to be ecologically significant (Rutherford et al. 2004, Kalny et al. 2017). In addition, the seasonal dynamics of macrophyte growth suggest that patchy areas of elevated water temperatures may occur early in the growing season when macrophytes are predominately submerged (Clark et al. 1999). Last, effective riverine canopies may be limited to systems that lack scouring flows (Chambers et al. 1991).

Modeling considerations

The role of the riverine canopy in water-temperature dynamics leads to important considerations for model development. Simulating seasonal emergent growth was a critical component in the 2-D numerical hydrodynamic and watertemperature model because of the effect of the riverine canopy on water temperatures in Big Springs Creek. Meaningful results were reproduced only when aquatic macrophyte characteristics (i.e., roughness and shade) were explicitly incorporated. These results further support the hypothesis that the riverine canopy affects the timing and variability of maximum water temperatures in Big Springs Creek.

However, the results also illustrated areas where future studies should improve upon the current understanding of riverine canopies and how they are modeled. Streams that are dominated by this process may require 2-D models to replicate aquatic macrophyte density and distribution sufficiently. This requirement would add to the monitoring, data, and computation requirements of a study. Temporal refinement is another area that would benefit from additional insight. Two configurations (pre-emergence and postemergence) were sufficient to capture the general process. However, a coarse representation may not be sufficient for management decisions that target specific periods, such as the period of rapid change during the early growing season, which is coincident with periods of potentially elevated water temperatures. Defining the management objective is critical to determining the appropriate level of spatial and temporal detail included in a simulation of a riverine canopy.

Management implications

The management implications for this riverine canopywater-temperature dynamic in Big Springs Creek are extensive. Cattle grazing, which was the primary cause of degraded stream habitat and elevated water temperatures in Big Springs Creek before restoration activities, has been estimated to degrade ~80% of stream and riparian systems in arid environments (Agouridis et al. 2005). The actual geographic scope of degradation may be higher once the systematic removal of the riverine canopy via livestock grazing is taken into account. Groundwater spring flows, channel geometry, and meteorological conditions are not factors that are easily, or even possibly, manipulated to change water temperatures to address this degradation. Aquatic macrophytes are more easily managed as part of a restoration strategy to improve water temperatures. Other approaches to providing shade along spring-fed creeks, like extensive riparian plantings, may be effective in the long-term, but probably would require decades to meet shading objectives (Caissie 2006). In comparison, passive recovery via aquatic macrophyte growth provides considerable short-term benefits, and should be considered in other waterways exhibiting emergent macrophyte growth.

The natural water-temperature patterns observed in Big Springs Creek also suggest that additional restoration or water-management actions may be advisable during the spring period before the shading influence of the riverine canopy develops. In Big Springs Creek, this period of maximum heating coincides with the early rearing stages of recently emerged juvenile salmonids that are relatively vulnerable to the effects of exposure to elevated water temperatures (Marine and Cech 2004, Ebersole et al. 2006). Additional work based on the 2-D hydrodynamic watertemperature model is underway to assess how water management alternatives could further ameliorate elevated water temperatures during the critical spring period.

Our study illustrates another important contribution by spring-fed streams, such as Big Springs Creek, to the longterm viability of coldwater species. Annual maximum water temperatures in Big Springs Creek occur in late spring and were measured 3.6 km downstream from coldwater sources. After emergence of the riverine canopy, stream temperatures generally remained below the recommended thresholds for juvenile Coho Salmon (USEPA 2003). This suggests that Big Springs Creek provides extensive, reach-scale coldwater habitat during a critical late-summer period when such habitat is typically limited in this watershed. Maintaining the passively restored condition is critical to supporting robust and resilient coldwater habitat, a key component of the long-term recovery and sustainability of coldwater fish like Coho Salmon.

The seasonal dynamics of aquatic macrophyte growth on water temperatures has important implications for regulatory management of Big Springs Creek. Big Springs Creek can influence water temperatures for tens of km downstream from its confluence with the Shasta River (Nichols et al. 2014). Water temperatures have been identified as the key impairment limiting the survival of anadromous fish in the Shasta Basin. Spatially explicit total maximum daily loads (TMDLs) (NCRWQCB 2006) and single-value thresholds (Stenhouse et al. 2012) have been recommended to address thermal habitat degradation in the Shasta Basin, specifically for the federally threatened Coho Salmon. However, these regulatory criteria do not account for the seasonal changes in the rate of stream heating or potential effects of reduced velocities on the downstream extent of water exported from Big Springs Creek. Thus, conventional management or conservation actions may not be effective because Big Springs Creek has an anomalous water-temperature dynamic.

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Author contributions: ADW developed the concept of the riverine canopy; designed, implemented, and maintained the monitoring program; developed the hydrodynamic and watertemperature models; analyzed empirical data and modeling results; and was the primary author of the manuscript. ALN collected and contributed the aquatic macrophyte biomass, channel hydraulics, hydrology, and channel geometry data; provided data analysis; and made substantial contributions to early drafts of the manuscript. EJH performed statistical analyses on model results and provided feedback and reviews for the manuscript. CAJ assisted in data collection for aquatic macrophyte biomass, channel hydraulics, and hydrology data; and provided feedback and reviews for the manuscript. ACF and CAB collected and contributed macrophyte distribution and assemblage data, as well as provided feedback and reviews for the manuscript. MLD assisted in the design of the monitoring program; implementation, application, and analysis of the hydrodynamic and water-temperature models; and provided feedback and reviews of the manuscript.

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