RIVER RESEARCH AND APPLICATIONS

River. Res. Applic. (2009)

FLOW AND WATER TEMPERATURE SIMULATION FOR HABITAT RESTORATION IN THE SHASTA RIVER, CALIFORNIA

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ABSTRACT

Low instream flows and high water temperatures are two factors limiting survival of native salmon in California's Shasta River. This study examines the potential to improve fish habitat conditions by better managing water quantity and quality using flow and water temperature simulation to evaluate potential restoration alternatives. This analysis provides a reasonable estimate of current and potential flows and temperatures for a representative dry year (2001) in the Shasta River, California. Results suggest restoring and protecting cool spring-fed sources provides the most benefit for native salmon species from a broad range of restoration alternatives. Implementing a combination of restoration alternatives further improves instream habitat. Results also indicate that substituting higher quality water can sometimes benefit native species without increasing environmental water allocations. This study shows the importance of focusing on the limitations of specific river systems, rather than systematically increasing instream flow as a one size fits all restoration approach. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: environmental water; instream flow; modelling; restoration; salmon; Shasta River; simulation; water temperature

Received 31 January 2009; Revised 16 April 2009; Accepted 21 May 2009

INTRODUCTION

Historically, much of California's Shasta River was dominated by numerous cold water springs, providing ideal, year-round, cool water habitat for coho and Chinook salmon and steelhead trout. Today, surface water diversions, groundwater pumping and construction of Dwinnell Dam have greatly decreased instream flow and habitat access, while low flow conditions, loss of riparian vegetation, tailwater return flow and lack of management of spring sources have substantially increased dry-season water temperatures (NRC, 2004).

Considerable research and analysis has been undertaken in the Shasta River Basin (CDFG, 1997; Abbott, 2002; Deas *et al*., 2003; NRC, 2004; Deas *et al*., 2004; Geisler, 2005; Jeffres *et al*., 2008). This study builds on that knowledge by using flow and temperature simulation modelling to analyse restoration alternatives which improve habitat conditions for native anadromous fish by increasing instream flow and/or decreasing water temperature. Modelling a range of flow and temperature management alternatives helps improve understanding of system response, and provides a framework to evaluate potential restoration alternatives at reach and basin-wide scales. This contributes to water planning and management decisions through evaluation and implementation of aquatic restoration prescriptions.

Flow and water temperature studies have been undertaken on many river systems to improve understanding of the effects of variable flow regimes on water temperature, and how water temperature affects survival of aquatic organisms. Numerical temperature modelling has been done for decades, although flow and water temperature models have become more refined in recent years (Caissie, 2006). Water temperature models have demonstrated that removing riparian vegetation increases stream temperatures (Brown, 1970; Rutherford *et al*., 1997; Bartholow, 2000), and that low flow conditions reduce thermal mass and increase instream temperatures (Bartholow, 1991; Conner *et al*., 2003). Some studies have linked thermal conditions with fish habitat. For example, Conner *et al*.

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(2003) reported more Chinook salmon in Idaho's Snake River survived with increased instream flows and cooler water temperatures. Bartholow (1991) showed that water diversions contribute to elevated instream temperatures, and higher instream flow maintained water temperatures below lethal thresholds for rainbow and brown trout on the Cach la Poudre River in Colorado.

A general understanding of hydro-ecological relationships has been reported in the literature, including recognition that a range of flows can often improve aquatic ecosystem function, with magnitude, duration, flashiness, timing and quantity of flow as important elements in a flow regime (Richter *et al*., 1997; Bovee *et al*., 1998). However, broad relationships and indices are not uniformly applicable to all systems and site-specific analysis is often required. Where the relationships between flow and ecological health are poorly understood, instream flow and river rehabilitation decisions are often determined by expert or political opinion, and may not provide the intended results (Acreman and Dunbar, 2004). Also, more is understood regarding surface water in rivers, although the more stable flow and temperature regimes of groundwater-dominated systems call for distinct management approaches (Sear *et al*., 1999).

This paper describes a specific case study using California's Shasta River to apply site specific, quantitative evaluation of instream flow and water temperature to a situation where high water temperature currently inhibits survival of native salmon species. Alternative flow regimes are based on a range of potential actions including prescribing minimum instream flows, reducing diversions and restoring spring-fed base flow. Also, a non-flow related prescription where riparian shading is increased as a temperature management strategy is evaluated. Further, an 'unimpaired' conditions alternative is simulated representing the undeveloped watershed. These alternatives as well as combinations of these prescriptions are compared to an 'existing' conditions simulation. For this study, flow is assessed primarily for effects on water temperature, such as reducing travel time and increasing thermal mass. Instream flow plays a vital role in geomorphology, benthic processes and habitat access, and different flow levels may influence useable habitat in ways not addressed here, such as threshold discharges, ideal flow ranges for spawning conditions and other biotic and ecological habitat considerations (Bovee *et al*., 1998; Gore and Nestler, 1988).

The tradeoff between additional flow and reduced water temperature is evaluated using a scenario-based approach to quantitatively assess how much water the Shasta River needs to meet goals of restoring native fisheries at selected locations and critical times of year. Managing multiple traditional and environmental water uses is a common source of conflict that occurs throughout much of the world where water is scarce. Where less water is used for environmental purposes, more can be used for traditional agriculture. This study offers an approach to restore natural systems while considering human water uses, and to focus restoration on water temperature where it is limiting.

The Tennessee Valley Authority's River Modelling System (TVA-RMS v.4) was used to simulate flow and water temperature for 2001, a dry year. RMS is described and assumptions are explained, with emphasis on necessary input data. RMS has previously been applied to the Shasta River for weeklong intervals to evaluate methods to reduce instream water temperature (Abbott, 2002; Deas *et al*., 2003; Geisler, 2005).

Uncertainty is inherent in modelling, but this analysis provides reasonable estimates of current and potential flows and temperatures for a representative dry year in the Shasta Basin, and helps identify and screen potential options to enhance instream flow and water temperature conditions for native salmon species. Through quantifying instream flow and water temperature improvements, restoration actions can be ranked and poor alternatives dismissed. This approach allows examination of instream flow and water temperature conditions by reach, indicating sections that are instrumental for river rehabilitation. Discussion includes ideas for future basin-wide management of the Shasta Valley to preserve human and environmental water uses, possible implications for restoration and water resource management in the larger Klamath River watershed and the importance of protecting cool water sources for salmon habitat.

SHASTA RIVER BACKGROUND

The Shasta River, in California's Siskiyou County, is a tributary to the Klamath River. It is the last major tributary below Iron Gate Dam, the most downstream impoundment on the Klamath River. Because migratory fish no longer

DOI: 10.1002/rra

have access above Iron Gate Dam, the Shasta River and other Klamath River tributaries are of greater importance to migratory salmon for spawning and rearing. Instream conditions in the Klamath River limit survival of certain salmon species and life stages, such as coho salmon spawning and rearing (Moyle, 2002). Enhancing habitat in Klamath River tributaries, such as the Shasta River, may provide promising options to improve survival of native salmon in this basin (NRC, 2004). In light of a recent agreement to remove mainstem dams on the Klamath River, major tributaries below Iron Gate Dam should be viewed as a high priority for restoration to ameliorate impacts of dam decommissioning activities.

The Shasta River watershed is approximately 2070 km^2, and flows northward approximately 113 km from its headwaters in the Scott Mountains to the Klamath River (Figure 1). The Shasta River is steep in its headwaters, then flows through a large, lower gradient alluvial valley and finally cascades through a steep canyon before joining the Klamath River. Precipitation averages 25–46 cm/yr in the Shasta Valley, mostly as winter rain and snowfall. Mean annual unimpaired runoff is approximately 168 000 000 m^3. This contribution to the Klamath River is usually insignificant, less than 8% of annual runoff below Iron Gate Dam (downstream of the Shasta River confluence), and less than 6% of summer runoff below Iron Gate Dam (USGS, 2008). The Shasta River experiences low flows in summer through early fall in response to California's Mediterranean climate.

Land use in the Shasta Valley is primarily agriculture with some urbanization (NRC, 2004). Most agricultural land in the Shasta Valley is dedicated to beef production, including dry and irrigated pasture, alfalfa, and some grain production; and other land uses including industrial, recreational and wildlife uses (CDFG, 2008). Irrigation season is April to October, and during this period in certain years flow in the river can drop below 0.6 m^3/s.

Dwinnell Dam is the Shasta River's only major dam, and was constructed in 1928, impounding lake Shastina (Figure 1). The reservoir is owned and operated by the Montague Water Conservation District (MWCD) to store winter flows, with water rights of 74 000 000 m^3, although maximum operating capacity is 61 700 000 m^3. The reservoir and irrigation system lose more water to seepage than is delivered to downstream irrigators (NRC, 2004). Such losses may supplement groundwater recharge. Direct reservoir outflow includes seepage, controlled releases of up to 0.3 m^3/s and infrequent uncontrolled winter spills (e.g. 1964 and 1997) (Vignola and Deas, 2005). Below

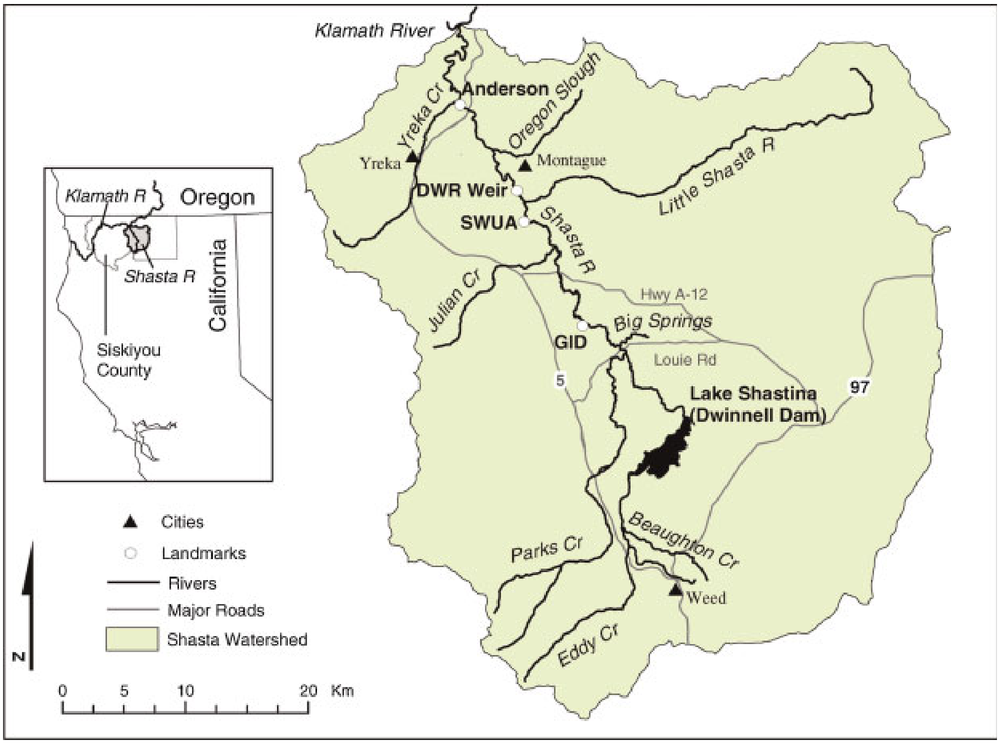

Figure 1. Shasta River watershed. This figure is available in colour online at www.interscience.wiley.com/journal/rra

DOI: 10.1002/rra

Dwinnell Dam, the Shasta River has four major tributaries: Parks Creek, Big Springs Creek, Little Shasta River and Yreka Creek (Figure 1). MWCD has an 18 500 000 m^3 water right from Parks Creek, diverting water from Parks Creek into the upper Shasta River above lake Shastina.

Four major diversions occur from the Shasta River, belonging to the Montague Water Conservation District (MWCD), the Big Springs Irrigation District (BSID), the Grenada Irrigation District (GID) and the Shasta Water Users Association (SWUA) (Figure 1). MWCD diverts water from Lake Shastina into the MWCD canal. BSID pumps groundwater upgradient of the Big Springs complex. The GID and Huseman Ditch (a moderate-size, private withdrawal) diversions are located jointly at RKM 49.2. Between April and October, diversions at the GID dam are approximately 0.6–1.2 m^3/s, depending on the amount delivered to the Huseman Ditch right holders and GID, the number of GID pumps operating, and water availability. The SWUA diversion is downstream of the Little Shasta River, and typically diverts 1.2 m^3/s from April to October.

Numerous small and moderate diversions along the length of the Shasta River are owned by individual landowners. Based on adjudicated water rights, maximum allowable diversions are approximately 3.2 m^3/s to landowners in the upper Shasta River above Big Springs, 5.0 m^3/s in the lower Shasta River, and 2.6 m^3/s to landowners along the Little Shasta River (CDWR, 2006). However, due to timing and priority order of the water rights, less water is typically diverted. The Shasta River has been largely adjudicated since 1934, although riparian water right owners are entitled to additional water not under Watermaster service (CDWR, 2006), and groundwater has not been adjudicated.

Local spring inflows modify the seasonal hydrograph below Big Springs Creek, although other springs provide modest baseflow upstream of Big Springs Creek. The Big Springs complex is largest in a series of spring complexes found along a north-south trending line in the southern Shasta Valley. The Big Springs complex forms the headwaters of Big Springs Creek, which travels approximately 3 km to enter the Shasta River at RKM 54.2, about 11 km downstream of Dwinnell Dam. Prior to water development, the springs contributed a constant flow of approximately 2.9 m^3/s of cool water to the Shasta River (Mack, 1960), approximately half of the 5.7 m^3/s estimated unimpaired baseflow (NRC, 2004). Today annual contributions from the Big Springs complex are approximately 2.0 m^3/s (NCRWQCB, 2006). At spring sources, year round water temperatures are approximately 11–12°C. However, diversion of spring sources, poor tailwater management, and lack of riparian vegetation can raise water temperature to 25°C at the confluence with the Shasta River (NCRWQCB, 2006).

The Big Springs complex and additional smaller springs form an extensive spring system that historically made the Shasta River arguably the most productive salmon and steelhead river in California (Snyder, 1931). The spring-fed river provided cool summer water temperatures and relatively warmer winter temperatures, ideal for salmonids (NRC, 2004). In general, groundwater-dominated river systems, like the Shasta River, have a more stable flow and thermal regime than those dominated by surface water (Sear *et al.*, 1999). The mainstem Shasta River could be either notably warmer, nearly the same, or considerably cooler than the spring-fed sources, depending on the time of year.

Aside from springflows, meteorological conditions drive thermal conditions in the Shasta River, and play a more prominent role in heating under low flow conditions. Low flows, prevalent during the summer irrigation season, increase water temperature because a shallow river has less thermal mass, relatively more surface area, and a longer travel time to the mouth, allowing atmospheric heating to have a more profound effect. Solar radiation effects are compounded by the current lack of shading by riparian vegetation due to grazing. Riparian vegetation absorbs and filters solar radiation, which can provide 95% of the heat input to a river at midday during the summer (Brown, 1970). Efforts are underway to fence the riparian corridor to reduce grazing of vegetation.

Fall-run Chinook (*Oncorhynchus tshawytscha*), coho (*O. kisutch*) and steelhead (*O. giardneri*) are present in the Shasta River (spring-run Chinook were extirpated with construction of Dwinnell Dam) (Moyle, 2002). The numbers of the three remaining species have declined drastically over the past century, primarily from elevated water temperature and low flow conditions. Coho were listed as federally threatened by the National Marine Fisheries Service in 1997 (Moyle, 2002). From 2001–2007, coho averaged 187 returning fish per year in the Shasta River (although high flows have compromised data collection and counts may not be complete), and Chinook averaged approximately 4566 returning adults from 2001–2006 (CDFG, 2008). Steelhead population counts have not been monitored closely but had dropped to an estimated 1700 fish in 2002 (CDFG, 2003). Preferred water temperatures for juvenile coho, Chinook and steelhead are 12–14, 13–18 and 15–18°C, respectively (Moyle, 2002).

Temperatures above 22–23°C are generally considered lethal for these species, although mortality is affected by food availability, length of elevated water temperature, thermal refuge availability and nightly minimum water temperature (Moyle, 2002).

METHODS

Model description

RMS was used to simulate flow and water temperature in the Shasta River. RMS is a one-dimensional (longitudinally), physically based numerical model composed of modules for hydrodynamics (ADYN) and water quality (RQUAL) (Hauser and Schohl, 2002). This application used a 1 h time step, and a variable spatial scale with node spacing ranging from 10–660 m to accommodate the sinuosity of the stream.

ADYN (hydrodynamics module). ADYN simulates hydrodynamic flows in mainstem and tributary channels, channel junctions and distributed or point lateral inflows at tributaries (Hauser and Schohl, 2002). The Shasta River was modelled as one continuous reach with tributaries as point inflows, large diversions as point diversions and smaller accretions and depletions as distributed flows. ADYN solves one-dimensional forms of conservation of mass and momentum equations (St. Venant equations for unsteady flow) for depth and velocity using a four-point implicit finite difference scheme with weighted spatial derivatives. Governing equations and associated details for ADYN are found in Hauser and Schohl (2002).

The input to run ADYN includes channel geometry (channel cross sections, elevations and bed slope), roughness coefficients, initial conditions, upstream and downstream boundary conditions, lateral inflows and diversions (Figure 2) (Hauser and Schohl, 2002).

RQUAL (water quality module). Upon completion of hydrodynamic simulation, velocities and water depths throughout the model domain are passed to RQUAL, the water quality module (Figure 2). RQUAL solves the mass transport (advection/diffusion) equation employing a Holly-Preissman numerical scheme using the same geometric representation as the hydrodynamic model. This module simulates the fate and transport of heat energy to represent water temperature (Hauser and Schohl, 2002).

Water temperature is modelled using physically based heat budget representation, including net heat exchange at the air-water and bed-water interfaces under specified meteorological and riparian shading conditions. Diffusion and topographic shading are not represented in RQUAL. Neglecting dispersion implies that this model is most appropriate for systems where transport is the primary mechanism and diffusion processes do not dominate. The Shasta River is largely dominated by advective processes. Topographic shading does not greatly influence water temperature in the Shasta River, except perhaps in the lower canyon reach.

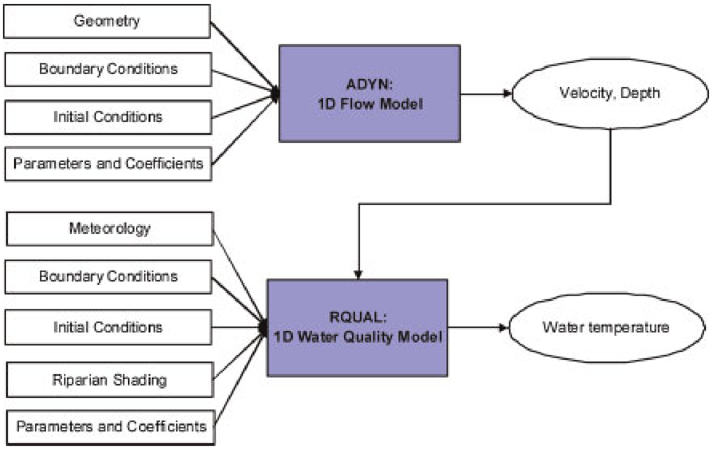

Figure 2. ADYN and RQUAL flow chart. This figure is available in colour online at www.interscience.wiley.com/journal/rra

DOI: 10.1002/rra

Application to California's Shasta River

RMS has been applied to the Shasta River in two earlier studies examining instream flow and water temperature. Those studies simulated the Shasta River for three 6-day periods in July, August and September of 2001 and 2002 (Abbott, 2002; Deas *et al*., 2003; Geisler, 2005). Sensitivity analysis was conducted for the Manning's roughness coefficient, contraction and expansion coefficients, wind coefficients and evaporative heat flux coefficients. Simulations were completed with ADYN for steady-state flows ranging from 0.06–5.7 m^3/s to evaluate model performance. Similarly, water temperature response to flow, tree height and transmittance changes was simulated with RQUAL. Model parameters and coefficients are listed in Geisler (2005) and Null (2008). The calibration and sensitivity analyses performed in those studies confirmed that RMS was adequately suited to the work undertaken here.

Geometry. The Shasta River was represented with 999 nodes from Dwinnell Dam to the confluence with the Klamath River, a modelled length of 65.4 km. Nodes were not evenly spaced, meandering reaches had a higher density of nodes than straighter reaches. Each RMS node has an accompanying five-point channel cross-sectional geometry. Full methodology is presented in Null (2008), Geisler (2005) and Abbott (2002).

Meteorology. Meteorological data are identical for all simulations. Dry bulb temperature, atmospheric pressure, wind speed, solar radiation and relative humidity were obtained from California Department of Forestry's Brazie Ranch station (CDEC). Dew point temperature was calculated from relative humidity, dry bulb temperature and elevation.

Current conditions input data (CC)

Hydrology. The current conditions model includes hydrology estimates for Dwinnell Dam releases, the GID and SWUA diversions, and point source tributary inflows at Parks Creek, Big Springs, Little Shasta River and Yreka Creek. Accretions and depletions representing numerous small and moderate diversions, tailwater return flow, accretions from groundwater, unquantified seepage, evaporation and overland flow along the Shasta River were modelled as distributed inflow for four reaches between Big Springs and Anderson Road (Figure 1). 2001 was used to reconstruct a current conditions hydrology because the period had the most measured data. Hydrology estimates were derived from measured data from the NCRWQCB or the California Department of Water Resources (CDEC) when available. Time periods without measured data were estimated by water balance or as a percentage of unimpaired flow. Null (2008) provides more discussion of input data and underlying assumptions. For all locations, hourly records were aggregated to average daily flow.

Water temperature boundary conditions. Water temperature boundary conditions were needed for Dwinnell Dam, Parks Creek, Big Springs, Little Shasta River and Yreka Creek. Other reaches with diversions, accretions, or depletions used simulated temperatures. Measured water temperature data were used as model input when available (Table I). Where temperature records were not available, water temperatures for current conditions were estimated by equilibrium temperature theory (Martin and McCutcheon, 1999), using a spreadsheet model. Brazie Ranch meteorological data were used to calculate hourly net heat flux at the air-water interface. Net heat flux is the sum of solar radiation, atmospheric long wave radiation, long wave back radiation from the water surface, evaporative heat flux and sensible heat flux. Hourly change in water temperature was then calculated using net heat flux, surface area and given water properties such as density and specific heat capacity. Depth ranged between 0.2–0.6 m to represent shallow tributary conditions.

Table I. Current conditions measured water temperature data availability (NCRWQCB, 2004)

Boundary condition	Measured data (2001) (dd/mm)	Measured location
Below Dwinnell Dam	24/4–13/10	Above Parks Creek
Parks Creek	24/4–13/10	Parks Creek
Big Springs	24/5–16/11	GID
Little Shasta River	Unavailable (compared to 20/6/2003–20/10/2003 data)	Little Shasta River

DOI: 10.1002/rra

Equilibrium temperatures were increased during winter (October–April) because estimated boundary condition temperatures hovered near 0°C during winter, which is cooler than recent winter water temperature measurements indicate (Null, 2008). The increase in winter water temperatures helped account for spring influences downstream of Big Springs Creek (springs are 11–12°C).

Riparian shading. Tree height was assumed to be 6.7 m with variable solar transmittance densities. Lowney (2000) estimates deep riparian foliage may transmit 10–20% of solar radiation through the canopy, and remaining solar radiation is absorbed or reflected by vegetation. However, riparian vegetation sampling completed in 2002 indicates vegetation along the Shasta River is not continuous and does not form a complete canopy. For this reason, we varied solar transmittance between 50–100% on both banks as a conservative estimate. Riparian shading was the same for all simulations, except the unimpaired and riparian shading alternatives.

Unimpaired conditions input data (UIM)

Pre-development conditions represent an estimate of the historic hydrology and thermal regime of the Shasta River prior to groundwater pumping, construction of Dwinnell Dam, stream impoundments, diversions and land use changes. Monthly flow input data (instead of daily) were used for unimpaired conditions because estimates on a finer temporal scale do not exist.

Hydrology. The model requires unimpaired hydrology estimates for the Shasta River at Dwinnell Dam, Parks Creek, Big Springs, the Little Shasta River and Yreka Creek. Unimpaired monthly inflow during summer (May–September) for Dwinnell Dam was derived from DWR Watermaster Service records (Deas *et al.*, 2004). DWR Watermaster service records from 1950–55 were used for the remaining months of the year because they include year-round data (typically Watermaster service records only include irrigation season observations). Average monthly flow data for Parks Creek and the Little Shasta River from May to September were taken from Shasta River unimpaired flows (CDWR Watermaster, 1930–1990; Deas *et al.*, 2004). For the remaining months, flows for Parks Creek and the Little Shasta River were estimated by water balance for each tributary. Big Springs records were derived from the Department of Public Works, Division of Water Rights water supply report (DPW-DWR, 1925). Flow for Yreka Creek was calculated by watershed area based on communication with the North Coast Regional Water Quality Control Board (NCRWQCB, 2006).

A seasonal depletion was included to balance the monthly flows at the mouth based on the DWR unimpaired flow study (CDWR, 1998). The Shasta River was assumed to experience a net loss to groundwater, evaporation and evapotranspiration of riparian vegetation from Dwinnell Dam to Yreka Creek (RKM 65.4–12.5). Losses were estimated to be 20% of the flow at the mouth from May to September, and 10% in the remaining months, values consistent with typical field losses (FAO, 1989). For all boundary inflows, daily data was linearly interpolated from monthly averages assigned to the middle of each month. This approach averaged winter peak flows, so short-term events were not represented and winter base flow during non-event periods was slightly higher.

Water temperature boundary conditions. Water temperature boundary conditions for the mainstem Shasta River at Dwinnell Dam, Parks Creek, the Little Shasta River and Yreka Creek were estimated for unimpaired conditions using the equilibrium temperature model discussed above. The equilibrium temperature model was calibrated to measured data at Parks Creek near its headwaters (NCRWQCB, 2004). Measured data were used in place of the equilibrium temperature when available (20/6–20/10). Water temperatures estimated with the equilibrium model were also adjusted to account for snowmelt from April 15 to July 15 (Watercourse Engineering, 2007).

The water temperature boundary condition for Big Springs was based on NCRWQCB data (NCRWQCB, 2004). We used a monthly average initial temperature of 11.3°C at Big Springs, with heating over a 6 h transit time to the Shasta River estimated with the equilibrium temperature model. For the unimpaired model, we assumed that the Big Springs complex had mature riparian vegetation.

Input data for additional model simulations

In addition to the current and unimpaired conditions simulations, five additional model simulations were used to assess instream habitat with various management alternatives. These additional model simulations modified input data from the current conditions simulation as noted in Table II.

DOI: 10.1002/rra

Table II. Simulations and changes to input data

Alternative	Abbreviation	Simulation assumptions		
		Flow	Temperature	Riparian vegetation
Current conditions	CC	Current conditions	Current conditions	6.7 m trees with 50–100% light transmittance
Unimpaired	UIM	Unimpaired	Unimpaired	10.7 m trees with 20% light transmittance
Minimum instream flows	MIF	Constant 0.9 m^3/s release from Dwinnell Dam	Current conditions	Current conditions
Remove Grenada Irrigation District diversion	GID	No water diverted at RKM 49.2 (1.0 m^3/s diverted under current conditions from 1/4–30/9)	Current conditions	Current conditions
Increase riparian vegetation	RV	Current conditions	Current conditions	Unimpaired
Restore Big Springs	BS	Approx. 0.9 m^3/s additional flow at Big Springs (RKM 54.2)	$10.4°C <= T_{w(BS)} <= 12.5°C$ (current conditions exceeds 20°C)	Current conditions
Remove Dwinnell Dam with restored upstream tributaries	DD	Unimpaired at damsite; Approx. 0.59 $m^3/s/day$ at Parks Creek	Unimpaired at damsite; current conditions at Parks Creek	Current conditions

Minimum instream flow (MIF). Minimum instream flows of 0.9 m^3/s from Dwinnell Dam to the Klamath River were simulated to explore the effect of increased flow on water temperature. A yearly release of 0.9 m^3/s requires over 25 900 000 m^3 from lake Shastina, nearly half its available storage.

Remove Grenada Irrigation District Diversion (GID). Many alterations to GID facilities have been proposed to improve instream habitat, including operating only one of GID's two pumps, no pumping and moving the diversion point downstream to Hwy A-12 at river kilometer 38.8 (TNC, 2005). There are two diversions at this structure—the GID diversion and the Huseman Ditch. For this analysis a diversion reduction of 1 m^3/s was assumed (i.e. eliminating GID and a portion of the Huseman Ditch diversion). Currently, GID has a junior water right on the Shasta River, and due to pumping costs, has the highest water price in the Shasta Basin at \$52/1230 m^3 (\$52/af) (TNC, 2005).

Increase riparian vegetation (RV). Aside from springflows, meteorological conditions largely drive thermal conditions in the Shasta River. Water temperature response to solar radiation varies seasonally, with maximum heating occurring during late spring and summer when there are long, sunny days. Riparian shading can considerably reduce thermal loading from solar radiation. 10.7 m is the average height of Arroyo Willow, one of the taller tree species surveyed during a 2001 Shasta Valley riparian vegetation assessment (Abbott, 2002). Therefore, riparian vegetation of 10.7 m trees with 20% solar transmittance was modelled to illustrate the maximum potential of riparian shading.

Restore Big Springs (BS). The Big Springs complex contributes most of the spring-derived water to the Shasta River. As modelled, restoring the Big Springs complex increased flow and reduced water temperature at the confluence with the Shasta River. The model configuration assumed flow from the Big Springs complex was shaded, well channelized and flowed directly to the Shasta River with modest change in water temperature.

Remove Dwinnell Dam (DD). Removing Dwinnell Dam has been considered because the dam is aging, inefficient due to seepage and blocks access to 22% of upstream coho habitat (NRC, 2004). Other impacts below the dam include altering the flow regime, reducing geomorphically important peak winter and spring flows, narrowing the river channel and potentially impacting water quality (Jeffres *et al*., 2008). Estimated unimpaired flow and water temperature values at the Dwinnell damsite were used to model instream conditions without Dwinnell Dam. This assumed that upstream tributaries had also been fully restored. The early August temperatures assumed in the analysis were about 15°C, yet inflow temperatures for the Shasta River above the dam can be notably higher.

DOI: 10.1002/rra

Without restoration of tributaries, atmospheric heating from the headwaters to the damsite may not yield the cooler water assumed here.

Currently, up to 18 500 000 m^3 is diverted from Parks Creek to Dwinnell Dam each year (CDWR, 1965a, 1965b). For alternative DD, flow from Parks Creek was increased by 0.59 m^3/s per day (17 000 000 m^3/yr), except when this raised Parks Creek above unimpaired flow levels. Water temperature from Parks Creek was unchanged from current conditions because the flow increase was not sufficient to dramatically alter stream temperatures.

Model testing

The year-long current conditions simulation was calibrated and tested against available data for 2001 (Null, 2008). Simulated flow and water temperature were compared to measured data where available and mean bias, mean absolute error and root mean squared error calculated (Tables III and IV). Mean absolute error was less than 0.3 m^3/s for flow and 2°C for water temperature for all sites with measured data.

Model performance generally reflected availability of flow and temperature field data. Timing of daily temperature variations matched measured data well, except at GID, where modelled temperature occurred 2–4 h earlier than measured. We attributed this delay to locations of temperature loggers in the diversion impoundment. Simulated water temperature was colder during the winter than measured at all sites. RMS can under predict temperatures during winter when water temperatures are below approximately 10°C (personal communication, G. Hauser), although sensitivity analysis and the general accuracy of model results indicate RMS is a good fit for this study. Water temperature is not a limiting factor for anadromous fish during winter, so this is not a significant source of uncertainty for the purposes of this work.

Table III. Measured versus modelled flow statistics

	Mean bias	MAE	Average measured flow	RMSE	*n*
	m^3/s	m^3/s	m^3/s	m^3/s	
Parks	0.03	0.03	0.16	0.10	3129
GID	−0.13	0.21	2.25	0.27	2854
A-12	−0.06	0.21	2.30	0.27	3044
DWR Weir	0.00	0.07	2.97	0.11	8738
Anderson	−0.13	0.24	1.85	0.34	3241
Mouth	0.00	0.09	3.03	0.20	8737
Shasta Average	***−0.05***	***0.14***	***2.09***	***0.22***	***4957***

Table IV. Measured versus modelled water temperature statistics

	Mean Bias	MAE	RMSE	*n*
	°C	°C	°C	
Above Parks	0.00	0.00	0.00	4798
Park Creek	−0.96	1.48	2.00	4125
Louie Road	−0.09	1.90	2.27	6471
GID	0.57	1.82	1.31	4224
A-12	−0.44	1.29	1.66	7668
DWR Weir	−0.47	1.30	1.62	7670
Hwy 3	−0.15	1.40	1.72	4177
Anderson	−0.70	1.34	1.65	7671
Mouth	−0.98	1.73	2.07	8461
Shasta Average	***−0.36***	***1.36***	***1.59***	***6141***

DOI: 10.1002/rra

LIMITATIONS

Modelling limitations exist primarily as a result of simplifications inherent in modelling studies. Specific model limitations include overall data density; data continuity and quality; the process of reducing the river system from a continuous feature to a set of discrete model nodes; simplifying the physical conditions and operational actions for model representation; representing tributaries as point inflows versus independent systems where flow and transport under different restoration prescriptions may vary considerably; as well as other assumptions. Further, all political, legal and institutional implications of restoration alternatives were ignored here.

Channel geometry could be improved with additional physical measurements of surface width, depth and bank height at more sites along the Shasta River. Additionally, the modelled channel, as employed in the model, does not incorporate floodplain areas and may not accurately represent the stage and thermal response associated with flood flows. Small diversions, tailwater returns and most groundwater flow (percolation, infiltration, small springs and seeps) were lumped and modelled as accretions or depletions on a reach-scale. Quantifying groundwater flow and temperature, including the stability of groundwater contributions to base flow, would improve model representation and understanding of the Shasta River. Similarly further studies on tailwater contributions, such as timing, quantity and thermal variability are needed to more accurately quantify the cumulative effects of diversions and tailwater returns to the Shasta River, improving modelling efforts and aiding management decisions.

Detailed discharge and water temperature data below Dwinnell Dam and at major tributary confluences to the Shasta River would improve simulation results and advance understanding of the river. Parks Creek, the Big Springs complex, Little Shasta River, Oregon Slough and Yreka Creek are tributaries for which additional, long-term data would be useful because these major tributaries can exert strong influence on the discharge and temperature of the Shasta River. Representing these systems as discrete tributaries would notably increase the understanding of tributary contributions on transit time and thermal characteristics of the Shasta River.

RESULTS

Model simulations were completed with the modelling sets described above to analyse seven restoration alternatives (CC, UIM, MIF, GID, RV, BS, DD). Results from unimpaired and current conditions provide bookends for the potential range of flows and water temperatures in the Shasta River. Results from each restoration alternative are compared to the current conditions and unimpaired simulations, and the implications for instream flow and thermal conditions are analysed. To focus the discussion of results we reduce the river to four reaches: Dwinnell Dam to Big Springs Creek, Big Springs Creek to Highway A-12, Highway A-12 to the DWR weir and the DWR weir to the mouth. The upper reaches were more affected by regulation at Dwinnell Dam and spring inputs from Big Springs Creek, while the lower reaches exhibited cumulative effects of upstream conditions, land use activities and atmospheric heating.

Some alternatives, such as increasing riparian vegetation, explore restoration decisions that directly affect water temperature to improve understanding and guide local management decisions. Other alternatives, such as minimum instream flows and removing diversions, primarily increase instream flow and may reduce water temperature by increasing thermal mass, reducing air-surface interface and decreasing travel time. Finally, alternatives such as restoring the Big Springs complex and removing Dwinnell Dam increase instream flow while also reducing summer water temperature through augmenting flow with a cool water source. Analysis of all restoration alternatives sheds insight into whether increasing flow, reducing water temperature, or combinations of the two are most effective at improving instream conditions for native salmon. In this way, modelling identifies appropriate management and operational decisions, and provides a means for prioritizing and developing funding for environmental water applications.

Overall, results suggest restoring the Big Springs complex was the most promising restoration option because cool water contributions were preserved for instream uses. When cool water existed in the upper reaches of the Shasta River, other restoration alternatives, such as riparian shading or higher instream flows that shorten travel time more effectively reduced atmospheric heating and provided additional downstream benefit. Thus, a mix of restoration strategies was most effective for native salmon habitat enhancement. Substituting higher water quality (i.e. reducing water temperature in this study) enhanced habitat conditions without large environmental water

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allocations. Results imply modest instream flows were beneficial, and improving water quality was more effective than increasing flow for restoring fish habitat. More complex basin-wide operations regarding the locations and sources of agricultural and urban diversions may result in additional environmental protection without harming existing water users. For instance, diverting water from warm water sources such as the lower reaches of the Shasta River, warm tributaries, or warm reservoir sources would add complexity to water management strategies, but would allow current agricultural and urban water uses to continue while maintaining cool spring-fed sources for environmental uses. This could have wide-reaching implications for the long-term viability of Shasta Valley agriculture.

Current conditions

Results from the CC alternative indicate that Shasta River instream flow was heavily influenced by diversions and water development, with a marked decrease in flow during the April–October irrigation season (Figure 3a). In all but the wettest years, diverted Parks Creek flows and water from the Shasta River above Dwinnell Dam were stored in Lake Shastina. Releases to the Shasta River were limited to approximately 0.05 m^3/s leakage through dam drains, with summer releases up to 0.25 m^3/s to fulfill downstream water rights. Thus, downstream Shasta River flows exhibited only modest peaks from runoff associated with local storm events. Summer periods experienced extreme and persistent low flow conditions in the lower river, with flow consistently below 1.4 m^3/s from mid-May to late-September. Flows from springs to the Shasta River were remarkably resilient, with baseflow increasing with the end of irrigation in the first week of October. During winter, baseflow exceeded 3 m^3/s at GID and 5 m^3/s at the mouth of the Shasta River (Figure 3a).

Winter water temperatures were 5–10°C in the reach below Big Springs Creek due to spring-fed contributions (Figure 4a). However, water temperatures in the Shasta River exceeded springflow temperature by mid-April. In Big Springs Creek, flow depletion during late spring and summer, coupled with overall reduced riparian vegetation shading and degraded channel form (wide and shallow) resulted in rapid heating en route to the Shasta River. Overall, water temperatures increased longitudinally from low flows and sparse riparian vegetation. Summer maximum daily water temperatures in the Shasta River at GID were well above 20°C, and exceeded 30°C at the mouth.

Unimpaired conditions

The unimpaired simulation assumed conditions prior to water and land development in the Shasta River Basin, without Dwinnell Dam, groundwater pumping, water diversions, or tailwater return flow, and with moderate

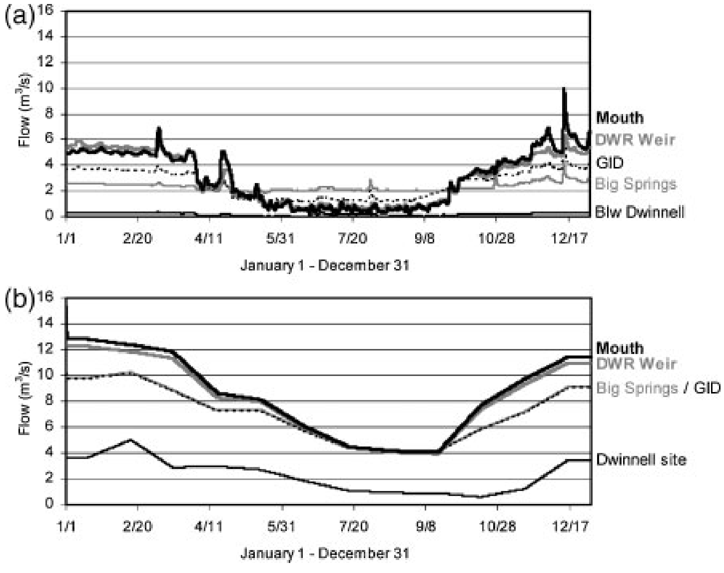

Figure 3. Simulated flows for select Shasta River locations: (a) current conditions and (b) unimpaired conditions

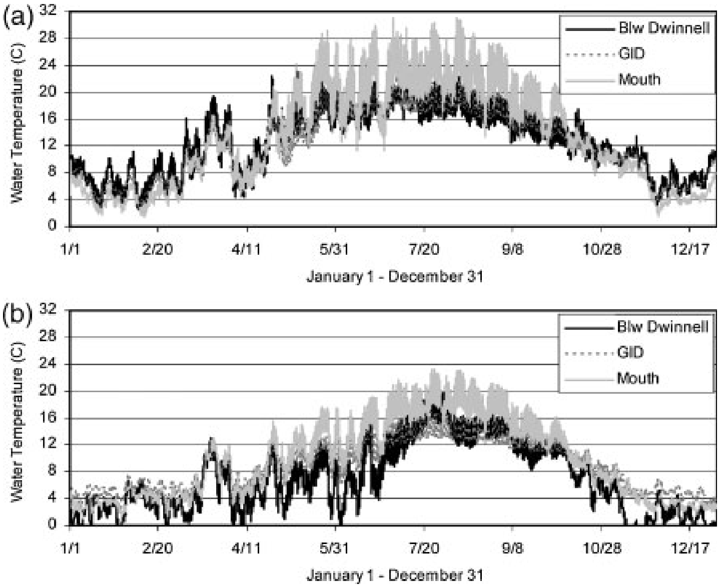

Figure 4. Simulated water temperatures for select Shasta River locations: (a) current conditions and (b) unimpaired

riparian shading, restored tributaries and channelized, shaded flow at Big Springs upstream of the Shasta River. Model output has no storm-related pulses because flow input data was from monthly estimates.

Results from simulated unimpaired conditions suggest average historic baseflow ranged from 1–4 m^3/s above Big Springs Creek, and flow steadily increased in the downstream direction (Figure 3b). Average modelled Shasta River winter baseflow exceeded approximately 8 m^3/s below Big Springs Creek, and historic data indicates flows greater than 14 m^3/s probably occurred following storms (Deas *et al*., 2004; CDWR Watermaster, 1930–1990). The simulated unimpaired flow regime would increase floodplain inundation during high flows in winter and spring, opening floodplain and side channel habitat for young salmon emerging from redds and rearing in the Shasta River. The stable modelled inflow from Big Springs maintained Shasta River baseflow above 4.3 m^3/s downstream of Big Springs throughout summer. Yearly low flow conditions on the Shasta River occurred in early autumn.

Simulated winter water temperature is probably a low estimate, due to the temperature moderating effect of springflow (Figure 4b). During spring and fall, Big Springs may have had a modest effect on water temperature because equilibrium temperature was close to the temperature of the springs from mid-September to late October, and April to May. During late spring and summer, local meteorological conditions heated the Shasta River from Big Springs Creek to the mouth, although riparian vegetation and increased thermal mass moderated this effect. During these periods, the cool water contributions from the springs were critical for maintaining moderate water temperatures in the mainstem Shasta River. Modelling results suggest that maximum spring and summer water temperatures remained well below 17°C at GID, and largely below 23°C at the mouth. At GID, minimum water temperatures were cooler than 12–13°C, providing relief for fish following warm, summer days.

Comparison of alternatives

Estimated hydrologic and thermal conditions of the Shasta River under potential restoration alternatives are compared in this section. In general, the Shasta River from Dwinnell Dam to the mouth is thermally-limited, meaning under current conditions, water temperatures (exacerbated by low stream flows, as well as other aforementioned factors) are the primary factor inhibiting salmon survival (NRC, 2004). Initial cool water conditions in the upstream reaches are necessary for restoration to be effective because it is easier to manage and maintain cold water than to cool warm water downstream. Additionally, a mix of alternatives, each collectively improving conditions, is most helpful to enhance instream habitat for native salmon species. Different restoration alternatives result in improvements to different reaches or during different seasons. It is important to work with fish biologists and local stakeholders to determine additional spatial and temporal needs of salmon species to ensure their survival. Habitat quality considerations other than instream flow and water temperature are ignored here.

Below Dwinnell Dam to Big Springs Creek. Historically, the reach from Dwinnell Dam (RKM 65.4) to the Big Springs complex (RKM 54.2) provided coho spawning and rearing habitat, although high water temperatures now inhibit coho rearing throughout summer. The CC, GID and BS alternatives all produce extreme low flow conditions in this reach (there was no difference between these alternatives in this reach) (Figure 5, SR at Parks Creek in Figure 6). MIF, DD and UIM all provide moderate instream flows in this reach. DD and UIM were unique in reducing the duration of dry summer conditions more than other restoration actions. For unimpaired conditions, weekly mean flow below 1.4 m^3/s persisted from July through mid-November, with weekly mean flow below 0.9 m^3/s from August through October (Figure 5). Thus, to improve instream flow conditions below Dwinnell Dam and above Big Springs, releases from Dwinnell Dam or removing the dam were instrumental to increase flow, with dam removal resulting in more natural seasonal effects on flow conditions.

For this upper reach, the CC, GID and BS alternatives have the same results, with maximum weekly mean temperatures exceeding 22°C (Figure 7) and a maximum hourly water temperature of approximately 28°C in early August (SR at Parks Creek in Figure 8). The MIF simulation reduced maximum weekly mean water temperature to 20.2°C, and the RV simulation reduced maximum weekly mean water temperature to 19.9°C. DD and UIM reduced temperatures the most, producing maximum weekly mean temperatures of 19.6°C and 18.0°C, respectively. Additionally, the DD and UIM alternatives had a shorter period of peak temperatures than all other alternatives (Figure 7).

Big Springs Creek to SWUA diversion. The reach from Big Springs (RKM 54.2) to the SWUA diversion (RKM 28.7) is the upper section of the alluvial Shasta Valley where some spawning and rearing occurs (Jeffres *et al*., 2008). The Big Springs complex contributes considerable flow to the Shasta River, and GID and SWUA are large diversions, making this reach a complex region of appreciable accretion and depletion (Figure 5). Under current conditions simulation, this reach experienced the lowest instream flow of all alternatives analysed (Figure 5, A-12 in Figure 6). MIF, GID and BS all lead to similar flow conditions, with flow increased by 0.9–1.1 m^3/s from current conditions. The DD alternative resulted in similar annual minimum flow conditions as the BS alternative (Figure 6), although like the previous reach, low flow conditions occurred over a shorter period of the of time when

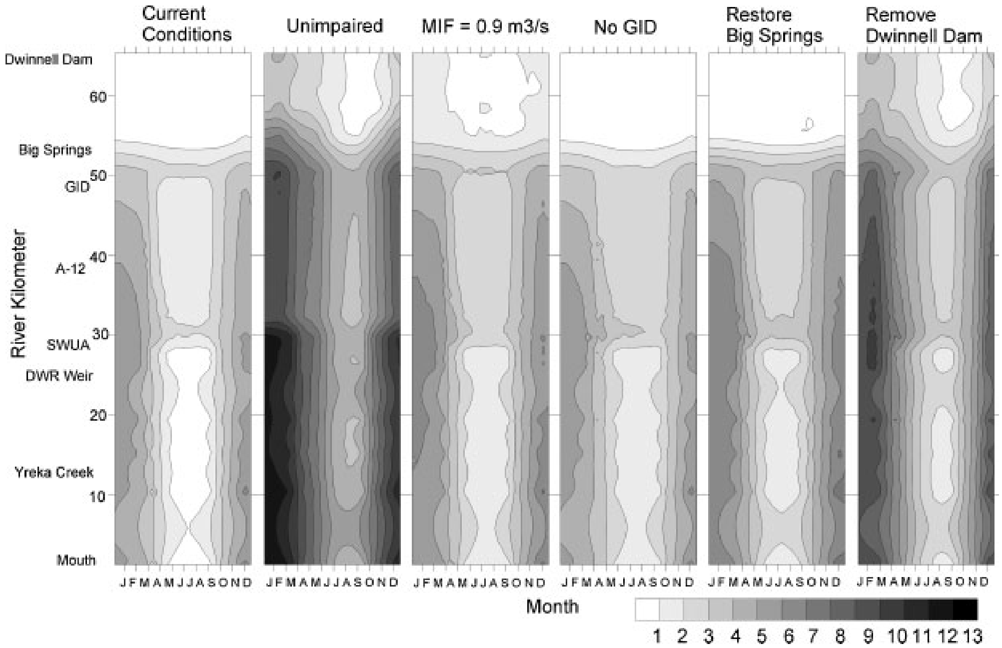

Figure 5. Simulated spatial and temporal weekly mean flow (m^3/s)

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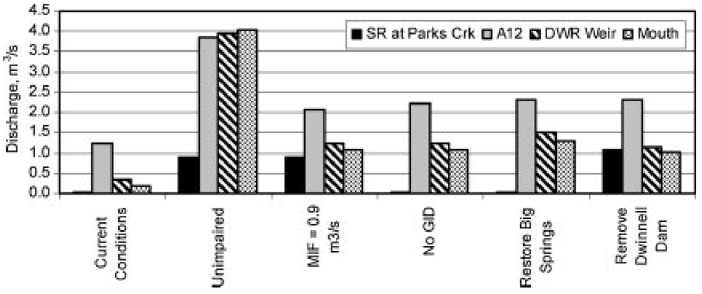

Figure 6. Simulated minimum hourly flow for restoration alternatives

Dwinnell Dam was removed (Figure 5). The UIM alternative showed a marked increase in flow during summer from BS or DD because all diversions were also eliminated.

Atmospheric heating increased water temperature longitudinally in all alternatives. This is consistent with water temperature monitoring conducted on the Nature Conservancy's Nelson Ranch (RKM 51.7–44.0) (Null, 2008). The CC case produced the highest water temperatures of all alternatives (Figure 7, A-12 in Figure 8). MIF, RV, GID and DD resulted in only minimal thermal improvements in this reach, indicating cool water sources are needed in the upper portions of the Shasta River or its tributaries for management alternatives to be most beneficial. Under the BS and UIM alternatives, the Big Springs complex had a stable thermal regime, with appreciable improvements to water temperature throughout this reach. Additionally, winter water temperatures were increased because springflow contributions were warmer than equilibrium river temperature, resulting in favourable winter rearing conditions for native salmon.

SWUA diversion to Yreka Creek. The reach between the SWUA diversion (RKM 28.7) and Yreka Creek (RKM 12.7) is in the lower part of the alluvial Shasta River Valley. Most large diversions are upstream, causing extreme low flow conditions in this reach during summer. Atmospheric heating exacerbated by low flows and minimal riparian vegetation raises temperatures longitudinally. Minimum annual flow and maximum annual water temperature are presented at the DWR weir (RKM 25.0) near the upstream end of this reach (Figures 6 and 8). Modelled annual weekly mean flow under current conditions reached a minimum of 0.43 m^3/s (Figure 5). The MIF, GID, BS and DD alternatives all maintained weekly mean flow of at least 1.3 m^3/s. Slightly higher winter flows

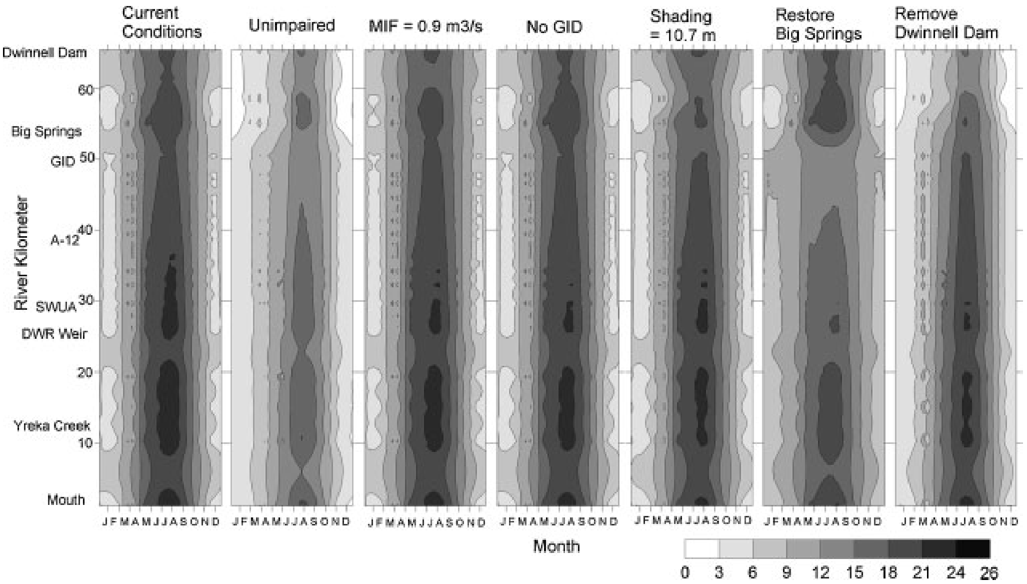

Figure 7. Simulated spatial and temporal mean weekly water temperature (C)

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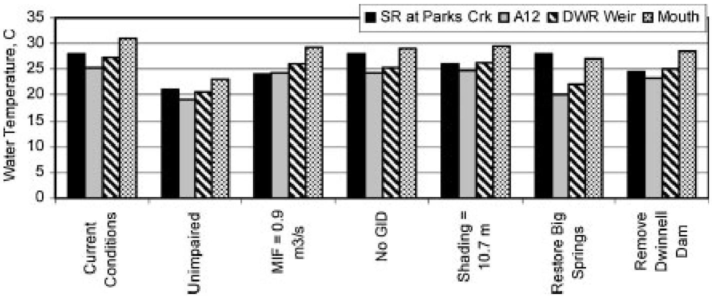

Figure 8. Simulated maximum hourly water temperature for restoration alternatives

occurred to some extent with the BS and DD alternatives, but were still substantially less than the 3.8 m^3/s that occurred in the unimpaired conditions simulation.

Current conditions resulted in a maximum weekly mean water temperature of 24.2°C at the DWR weir (Figure 7). All restoration alternatives caused only slight thermal improvements, with the exception of BS and UIM, which improve conditions for much of the Shasta River (Figures 7 and 8). Thermal conditions produced by the restored Big Springs simulation were better than all but the unimpaired simulation. This suggests a combination of restoration alternatives that simultaneously increase flow, protect cool water sources and shade the river from solar radiation will most improve instream conditions.

Yreka Creek to the mouth. All anadromous fish must migrate though the mouth of the Shasta River, although coho, Chinook and steelhead out-migrate by mid-July, and spawners generally do not enter the Shasta River until mid-September, largely avoiding months with the warmest conditions (CDFG, 1997; NCRWQCB, 2006). Flow conditions in this reach are similar to the previous reach. Modelled current conditions (CC alternative) minimum weekly average flow was 0.4 m^3/s (Figure 5), and hourly flow reached an annual minimum of 0.18 m^3/s on June 20 (Figure 6). The MIF, GID, BS or DD alternatives produced the greatest increase in flow at the mouth of the Shasta River. These alternatives raised flow at the mouth to a minimum weekly mean of 1.3–1.6 m^3/s (Figures 5 and 6).

Water temperatures in this reach are also similar to the previous reach, except slightly warmer due to continued atmospheric heating. Recorded and simulated water temperatures are consistently highest at the mouth (RKM 1.2). Maximum weekly mean water temperature was lowest under unimpaired conditions, at 19.5°C. The next best alternatives were BS, RV and DD, with maximum weekly mean water temperatures of 22.3, 23.5 and 23.9°C, respectively. Maximum weekly mean temperature exceeded 24°C for all other alternatives. Maximum weekly mean temperature increased 1.8°C between this reach and the upstream reach under the BS alternative, the largest increase of any scenario demonstrating water temperature at the mouth was farthest from equilibrium (temperatures were coolest) when the Big Springs complex was restored.

Summary of results. Historically, a considerable fraction of the Shasta River baseflow was derived from spring inflows, which provided persistent baseflow at consistent year-round water temperatures suitable for salmon. Flow was enhanced with rain and snow runoff from the upper Shasta River, Parks Creek and the Little Shasta River. Water temperature was influenced by the thermal regime of headwaters, tributaries and spring inflow. Springwater inflow was typically warmer than equilibrium river temperature during winter and cooler during summer. Atmospheric heating, primarily from solar radiation, influenced river temperature by accumulated heating longitudinally. Flows have now been altered and diminished by construction of Dwinnell Dam, surface water diversions and groundwater pumping, resulting in low instream flows in the Shasta River. Water temperature has increased due to diversion of spring-fed water, warm tailwater return flows, low flow conditions and reduced riparian shading.

Welsh *et al*. (2001) found that coho are present in tributaries to California's Mattole River when maximum weekly average water temperature (MWAT) is 16.7°C or less. Here, simulated water temperatures for a representative summer week (5/8/01–11/8/01) exceeded Welsh's ideal MWAT of 16.7°C in the lower reaches of the Shasta River under all alternatives (Figure 9). It is possible that historic MWAT water temperature exceeded 16.7°C in the Shasta River, but abundant food availability kept fish productivity high (Jeffres *et al*., 2008), or that water temperature exceeded 16.7°C in the lower reaches historically, and fish reared in the upper reaches of the Shasta River during the summer (including upstream of Dwinnell Dam). Model results suggest unimpaired conditions and

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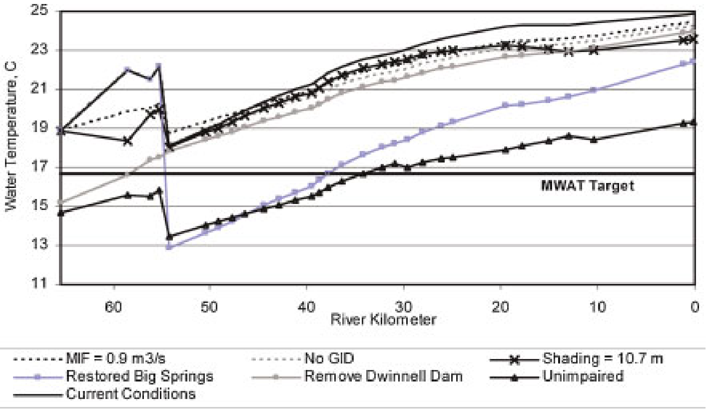

Figure 9. Longitudinal maximum weekly average water temperature (MWAT) under different restoration alternatives with MWAT target, 5/8/01–11/8/01. This figure is available in colour online at www.interscience.wiley.com/journal/rra

removing Dwinnell Dam provide adequate summer thermal conditions for coho for approximately 8 km immediately downstream of the damsite, and unimpaired conditions and restoring Big Springs provide approximately 20 km of optimal thermal conditions directly downstream of the Big Springs confluence. Water temperature remains above the 16.7°C target under all other alternatives.

Our results show a mix of restoration approaches provides more benefit to flow and temperature habitat conditions than any single restoration action, as illustrated by the unimpaired simulation. Cool water in the upper reaches of the Shasta River (below Dwinnell Dam or Big Springs) is required for restoration to be effective because maintaining water temperature is more feasible than cooling a warm river. Given cool water in the upper reaches, restoration options such as reducing water temperature by riparian shading or reducing travel time and increasing thermal mass by increasing flow (from restoring Big Springs, reducing diversions, minimum instream flows or dam removal) better maintain conditions longitudinally. If water temperature in the Shasta River is improved, spawning habitat and access around physical barriers would likely become the next factors limiting fish production in the Shasta River (Jeffres *et al*., 2008).

This study indicates that substituting higher quality water can potentially benefit native fish species without increasing environmental water allocations (i.e. quantity), when water quality is limiting. In this analysis, the Shasta River heated longitudinally at a similar rate when additional riparian shading reduced solar radiation as when thermal mass was increased by raising flow, implying that maintaining cool water is comparable to increasing instream flow.

DISCUSSION AND CONCLUSIONS

Determining how much flow rivers need to support ecosystems and natural processes is an ongoing branch of restoration science (Richter *et al*., 1997). We contribute to that knowledge by quantitatively assessing a specific river to understand how a range of restoration prescriptions provide thermal benefits for salmon. Analyses indicate that for the Shasta River, a minimum amount of water is required, and then there is a tradeoff between more flow and other actions which specifically target water temperature. This study shows that it is important to focus on the limitations of specific river systems, rather than systematically increasing instream flow as a one size fits all restoration approach. For the Shasta River, instream flow is most pertinent where it impacts or improves water temperature.

We described resulting instream flow and temperature conditions from each restoration action, so that alternatives can be ranked by improvement to instream habitat for native fish species. This approach highlights the most promising restoration actions for the Shasta River, such as protecting spring-fed contributions like Big Springs Creek. It also enables restoration alternatives to be evaluated on a reach by reach basis. This shows which reaches are most vulnerable to river regulation and development, and conversely which reaches are needed for restoration efforts. Restoring the upper reaches is likely imperative for fish habitat.

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Policy and management insights from this study include protecting cool water spring-fed water sources for fisheries and instream uses, and substituting warmer water supplies for agricultural uses. This thermal management shows promise for restoring the Shasta River, assuming water temperature does not detrimentally affect agricultural users. Potentially, local landowners could divert water from warm locations such as the lower reaches of the Shasta River, warm tributaries or perhaps reservoir supplies, with cool water sources reserved for environmental enhancement. Additional studies are needed to study costs of small water conveyance projects to allow this. It is possible that system-wide management of the Shasta River for water supply and environmental enhancement, as proposed here, could be cheaper than other restoration approaches which target providing cool water habitat in the lower reaches during summer while diverting the cool spring-fed sources in the upper reaches.

From a broader perspective, the Shasta River may be an instrumental component for meeting restoration goals in the Klamath Basin (Deas *et al*., 2004). In the past decade, water management has become a divisive issue in the Klamath Basin. This study shows that restoration alternatives for the Shasta River are unlikely to provide cool water contributions to the Klamath River because temperatures exceed 22°C at the confluence of the Shasta and Klamath River for all restoration actions except unimpaired conditions. Rather, restoring the Shasta River could provide spawning and year-round rearing habitat for coho, fall-run Chinook and steelhead trout. If aquatic habitat could be restored and local fisheries improved in the Shasta River, restoration efforts for the Klamath River could focus on maintaining adequate passage for migrating salmonids downstream of the Shasta River. This has the potential to reduce pressure for restoring the Klamath River upstream of the Shasta River, so that habitat enhancement scenarios, including dam removal decisions, can be well-studied and adequately understood prior to implementation.

Outside California, many arid regions face water allocation problems and rivers with degraded instream habitat from elevated water temperature. This study illustrates that the impacts of flow regime cannot be separated from water temperature. An integrated approach, as used here, is helpful for determining environmental flows and assessing instream habitat. In systems with groundwater contributions, protecting the cool spring-fed flows provides the most benefit to salmon species. This finding may be applicable to other groundwater-dominated systems, or rivers with cool-water sources (such as cold, hypolimnetic releases from large reservoirs). Protecting cool-water sources for instream habitat may become more important in coming decades due to climate warming. This study increases knowledge regarding methods to improve environmental and traditional water uses, and to focus restoration efforts on water quality where it is limiting. The results reported here suggest the following conclusions for enhancing instream flow and thermal conditions:

- For the Shasta River, cool water is needed in the upper river reaches (below Dwinnell Dam or near the Big Springs complex). Restoration and management options can then effectively maintain temperature. Without upstream cool water, most management alternatives become largely ineffective.
- Restoring the Big Springs complex improves conditions through much of the Shasta River, making this perhaps the most promising option for improving instream flow and temperature conditions.
- Overall, improving water quality can sometimes reduce instream flow needs for native salmon. Protecting cool groundwater flows from springs provides the most benefit to salmon species.
- Coordinated water management may enable cold spring-fed river reaches to be used for environmental enhancement, while maintaining traditional agricultural and urban water supplies from reaches with warmer water.
- A mix of restoration strategies provides the greatest improvements to instream habitat.
- Simulation modelling is useful for highlighting promising restoration alternatives and eliminating alternatives that may provide less environmental benefit.

ACKNOWLEDGEMENTS

This research was funded in part by the United States Environmental Protection Agency (EPA) under the Science to Achieve Results (STAR) Graduate Fellowship Programme. The views expressed herein may not reflect the views of

DOI: 10.1002/rra

the EPA. The authors thank Alida Abbott and Limor Geisler for previous work modelling the Shasta River, and two reviewers for their helpful comments on this manuscript.

REFERENCES

Abbott AGP. 2002. The effect of riparian vegetation on stream temperature in the Shasta River. *Master's Thesis*. U.C. Davis Dept. of Civil and Environmental Engineering.

Acreman M, Dunbar MJ. 2004. Defining environmental river flow requirements—a review. *Hydrology and Earth System Sciences* **8**(5): 861–876.

Bartholow JM. 1991. A modeling assessment of the thermal regime for an urban sport fishery. *Environmental Management* **15**: 833–845.

Bartholow JM. 2000. Estimating cumulative effects of clearcutting on stream temperatures. *Rivers* **7**: 284–297.

Bovee KD, Lamb BL, Bartholow JM, Stalnaker CB, Taylor J, Henriksen J. 1998. Stream habitat analysis using the instream flow incremental methodology. *Information and Technology Report USGS/BRD/ITR- 1998-0004*, C Geological Survey-BRD, Fort Collins, CO.

Brown GW. 1970. Predicting the effect of clearcutting on stream temperature. *Journal of Soils Water Conservation* **25**: 11–13.

Caissie D. 2006. The thermal regime of rivers: a review. *Freshwater Biology* **51**: 1389–1406.

CDEC (CA Dept. of Water Resources—CA Data Exchange Center). 2007 Available online http://cdec.water.ca.gov/. Accessed on 4/2007.

CDFG (CA Dept. of Fish and Game). 1997. *A Biological Needs Assessment for Anadromous Fish in the Shasta River, Siskiyou County, California*. CA Dept. of Fish and Game, Northern California-North Coast Region. Redding, CA

CDFG (CA Dept. of Fish and Game). 2003. *Shasta River Fish Counting Facility, Chinook and Coho Salmon Observations in 2002*. Siskiyou County, CA.

CDFG (CA Dept. of Fish and Game). 2008. Shasta river watershed-wide permitting program draft environmental report. Prepared by ESA. Available online: http://www.dfg.ca.gov/news/pubnotice/ShastaRiverEIR/. Accessed on 1/2009.

CDWR (CA Dept. of Water Resources) Watermaster. *1930–1990 Reports*. Shasta River Watermaster Service Area Reports.

CDWR (CA Dept. of Water Resources). 1965a. *Land and Water Use in Shasta-Scott Valleys Hydrographic Unit, Volume I: Text*. Bulletin No. 94–95.

CDWR (CA Dept. of Water Resources). 1965b. *Land and Water Use in Shasta-Scott Valleys Hydrographic Unit, Volume I: Plates*. Bulletin No. 94–95.

CDWR (CA Dept. of Water Resources). 1998. *Klamath River Basin Natural Flow*. Office Memo, March 13.

CDWR (CA Dept. of Water Resources) Watermaster Report. 2006. *Lower Shasta River, Upper Shasta River, and Little Shasta River Service Areas*. Available online (http://www.nd.water.ca.gov/PPAs/Watermasters/ServiceAreas/ShastaRiver/index.cfm). Accessed on 4/2007.

Conner WP, Burge HL, Yearsley JR, Bjornn TC. 2003. Influence of flow and temperature on survival of wild subyearling fall chinook salmon in the Snake River. *North American Journal of Fisheries Management* **23**: 362–375.

Deas ML, Abbott A, Bale A. 2003. Shasta River Flow and Temperature Modeling Project. Prepared for Watercourse Engineering, Inc. Sponsored by the Shasta Valley Resource Conservation District with funding by CDFG from the CA. *Coastal Salmon Restoration Program*, Napa, CA.

Deas ML, Moyle PB, Mount J, Lund JR, Lowney CL, Tanaka S. 2004. *Priority Actions for Restoration of the Shasta River—Technical Report*. Prepared for The Nature Conservancy. June 11.

DPW-DWR (Dept. of Public Works, Division of Water Rights, State of California). 1925. Water supply and use of water from Shasta River and tributaries, Siskiyou County, California. *Shasta River Adjudication Proceedings*.

FAO (Food and Agriculture Organization of the United Nations). 1989. Irrigation water management: irrigation scheduling. Available online: http://www.fao.org/docrep/T7202E/t7202e08.htm. Accessed on 1/2007.

Geisler L. 2005. Shasta River Flow, Temperature, and Dissolved Oxygen Model Calibration Technical Report. Prepared for ICE, UC Davis and NCRWQCB. UC Davis and Watercourse Engineering, Inc. Available online: http://www.waterboards.ca.gov/northcoast/programs/tmdl/shasta/060707/20AppendixDShastaRiverFlowTemperatureandDissolvedOxygenModelCalibrationTechnicalReport.pdf. Accessed on 5/2007.

Gore JA, Nestler JM. 1988. Instream flow studies in perspective. *Regulated Rivers: Research and Management* **2**: 93–101.

Hauser GE, Schohl GA. 2002. River Modeling System v4—User Guide and Technical Reference; Report No. WR28-1-590-164; TVA River System Operations and Environment. Norris, Tennessee.

Jeffres C, Buckland E, Kiernan J, King A, Nichols A, Null S, Mount J, Moyle P, Deas M. 2008. *Baseline Assessment of Salmonid Habitat and Aquatic Ecology of the Nelson Ranch, Shasta River, California: Water Year 2007*. Prepared for the California Nature Conservancy by U.C Davis Center for Watershed Sciences and Watercourse Engineering, Inc.

Lowney CL. 2000. River temperature dynamics in the Sacramento River: measuring and monitoring. *Ph.D. Dissertation*, U.C. Davis Dept. of Civil and Environmental Engineering.

Mack S. 1960. Geology and ground-water features of Shasta Valley, Siskiyou County, California. *U.S. Geological Survey Water-Supply Paper 1484*. U.S. Government Printing Office, Washington, DC.

Martin JL, McCutcheon SC. 1999. *Hydrodynamics and transport for water quality modeling*. Lewis Publishers: New York.

Moyle PB. 2002. *Inland Fishes of California*. University of California Press: Berkeley and Los Angeles, CA.

NCRWQCB (CA North Coast Regional Water Quality Control Board). 2004. *Shasta River Water Quality Conditions: 2002 & 2003—Draft for Public Review*. May.

DOI: 10.1002/rra

NCRWQCB (CA North Coast Regional Water Quality Control Board). 2006. *Staff Report for the Action Plan for the Shasta River Watershed Temperature and Dissolved Oxygen TMDLs*. Santa Rosa, CA. Available online (http://www.swrcb.ca.gov/rwqcb1/programs/tmdl/shasta/060707/staff-report-complete.pdf). Accessed on 6/2007.

NRC (National Resources Council). 2004. *Endangered and Threatened Fishes in the Klamath River Basin: Causes of Decline and Strategies for Recovery*. Committee on Endangered and Threatened Fishes in the Klamath River Basin, National Research Council. The National Academy Press.

Null S. 2008. Improving managed environmental water use: Shasta River flow and temperature modeling. *Ph.D. Dissertation*. U.C. Davis Geography Graduate Group.

Richter BD, Baumgartner JV, Wigington R, Braun DP. 1997. How much water does a river need? *Freshwater Biology* **13**: 231–249.

Rutherford JC, Blackett S, Blackett C, Saito L, Davies-Colley RJ. 1997. Predicting the effects of shade on water temperature in small streams. *New Zealand Journal of Marine and Freshwater Research* **31**: 707–721.

Sear DA, Armitage PD, Dawson FH. 1999. Groundwater dominated rivers. *Hydrological Processes* **13**: 255–276.

Snyder JO. 1931. *Salmon of the Klamath River, California. CA Dept. of Fish and Game Bulletin 34*. California State Printing Office, Sacramento, CA. Available at http://www.krisweb.com/biblio/klamath_cdfg_snyder_1931.pdf. Accessed on 5/2007.

TNC (The Nature Conservancy). 2005. *A Strategy for Enhancing Flow and Protecting Anadromous Fish Habitat in the Shasta River*. Prepared by Kat Ridolfi.

USGS (US Geological Survey). 2008. Real Time Water Data for California website. Available at http://waterdata.usgs.gov/ca/nwis/rt. Accessed on 7/2008.

Vignola E, Deas ML. 2005. *Lake Shastina Limnology, Watercourse Engineering, Inc.* Prepared for the UC Davis Information Center for the Environment and the North Coast Regional Water Quality Control Board. Davis, CA.

Watercourse Engineering. 2007. *Trinity River Flow and Temperature Modeling Project*. Prepared for Trinity County Planning Dept., Natural Resources Division and the Trinity River Restoration Program. USBR Cooperative Agreement No. 06FG230819.

Welsh HH, Hodgson GR, Harvey BC, Roche ME. 2001. Distribution of juvenile coho salmon in relation to water temperatures in tributaries of the Mattole River, California. *North American Journal of Fisheries Management* **21**: 464–470.

DOI: 10.1002/rra