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Incorporating thermal requirements into flow regime development for multiple Pacific salmonid species in regulated rivers

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ABSTRACT

It has long been recognized that altered flow regimes and warm water temperature are among major stressors that have contributed to the precipitous decline of salmonid populations in California's Central Valley, resulting in many of them being listed as endangered or threatened pursuant to the U.S. Endangered Species Act. While it is widely acknowledged that water temperature affects all freshwater life stages of salmonids, it has not been a focus when developing instream flow requirements. In this study, we developed a framework that incorporates water temperature requirements into flow regime development for multiple Pacific salmonid species. We applied this framework to Clear Creek, an upper Central Valley stream that supports three salmonid species and has been regulated by reservoir releases for instream flow since 1963 when Whiskeytown dam was built. The analysis of flow data indicated that from the pre-project (*i.e.*, pre-dam) period to post- project period, flow magnitude was reduced by 45–76% for flood flows, 43% for spring pulse flows, and 27–53% for monthly average flows from January through May. Water temperature from 1996 to 2013 exceeded the U.S. Environmental Protection Agency recommended criteria for salmonids from May to October, with most exceedances occurring in September, followed by May and October. Statistical analyses suggested that the abundances of both adult and juvenile salmonids in Clear Creek were strongly correlated to flow magnitude, water temperature, or both. Higher flows that coincided with adult immigration were correlated to higher numbers of adults spawning in Clear Creek, which in turn produced a higher number of juveniles; however, higher flows that occurred during the early life stages (*e.g.*, fry) appeared to reduce the number of outmigrating juveniles. Higher water temperatures in the immigration, spawning, and juvenile rearing periods were correlated with reduced numbers of both adult and juvenile spring-run Chinook salmon in Clear Creek. High water temperatures in June and July were correlated with reduced number of outmigrating juvenile steelhead. Adult or juvenile fall-run Chinook salmon showed either a curvilinear or linear relationship with water temperature during their immigration, spawning, and rearing periods. Based on the pre-project flow and strong correlation between fish abundance and flow or water temperature, we developed a flow regime that incorporates water temperature requirements and other needs of different life stages of salmonids. The flow regime includes the following elements: winter and spring base flow, summer and fall water temperature sustaining flow, winter floodplain inundation flow, and spring pulse flow. This approach can be applied to other regulated streams for developing flow regimes to conserve and recover listed salmonid species.

1. Introduction

California's Central Valley rivers and creeks historically were a significant source of salmonid production in California waters, but the populations of native Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*O. mykiss*) have declined dramatically. Increasing rates of decline followed construction of dams and reservoirs, which primarily occurred around the mid-1900s. Many of these water development projects completely blocked the upstream migration of Chinook salmon and steelhead to spawning and rearing habitats; spawning and rearing were therefore confined to river reaches downstream of the dams, where flow

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regimes were often altered and water temperatures were frequently impaired (Cummins et al., 2008; Brown and Bauer, 2009; National Marine Fisheries Service, 2014). Altered flows and warm water temperatures impact adult immigration, spawning, egg incubation, fry emergence, and juvenile rearing and outmigration (McCullough, 1999; Brown and Bauer, 2009; Kiernan et al., 2012; Zeug et al., 2014).

Recovery of these Endangered Species Act listed Central Valley salmon and steelhead populations requires a suite of long-term actions, including reintroduction of the fish to habitats historically accessible but currently blocked by dams (National Marine Fisheries Service, 2014). In addition, short-term remediation measures may include reservoir reoperation and habitat restoration to improve downstream flow, water temperature, and physical habitat for spawning, rearing, and migration of salmonids (U.S. Fish and Wildlife Service, 1995, 2001; Cummins et al., 2008). In this study, we developed a systematic framework for incorporating water temperature requirements into flow regime development for multiple salmonid species. We applied the framework to Clear Creek, a stream near Redding, California. Clear Creek was selected in this study because it (1) supports three salmonid species; (2) has a comprehensive monitoring program for fish, flow, and water temperature; and (3) is regulated for flow almost entirely by reservoir release.

Our framework for assessing streamflow is based largely on the methodology developed by an independent review committee that had considerable experience in developing flow criteria and implementing these criteria in Florida, Texas, and California (Dahm et al., 2014). The methodology is intended to be scientifically defensible, cost-effective, representative at the watershed scale, and timely relative to implementation. It is aimed to addresses multiple species, different life stages, and different fluvial processes in a watershed. The integral parts of the methodology are to determine how and to what degree (1) past and present water management has altered stream flows, (2) the altered flows have affected river ecosystems and associated aquatic biota, and (3) the altered flows may be restored to some level mimicking a natural flow regime in order to reduce the effects that have resulted from the past flow alterations (Richter et al., 1996; Poff et al., 1997; Arthington et al., 2006; Petts, 2009).

To further the methodology, our framework explicitly considers water temperature requirements for salmonid species and integrates water temperature-sustaining flows into instream flows. While the ecological and biological significance of water temperature in riverine ecosystems is widely acknowledged (Richter and Kolmes, 2005; Caissie, 2006; McCullough, et al., 2009; Olden and Naiman, 2010), mitigating for water temperature impairment below dams has received much less attention in the development of instream flows. Clearly, both flow and water temperature are important for aquatic ecosystems and must be simultaneously considered for the successful implementation of instream flow criteria below dams. Without considering water temperature, the resulting flows would be incomplete, reducing the likelihood of successful conservation of focal species. This study is intended to fill this major gap in instream flow development. We illustrate the development of flow regimes that integrate both flow and water temperature requirements for anadromous salmonid species. We first present the natural flow before Whiskeytown Dam was built in Clear Creek and assess changes in flows before and after the dam was complete. We then analyze water temperature data and develop a model to estimate the amount of water needed to meet water temperature requirements downstream of the dam. Finally, we describe the process of developing a flow regime that integrates water temperature requirements for salmonids.

2. Study area

The Clear Creek watershed, 56 km long with a drainage area of 616 km^2, is a tributary to the upper Sacramento River, the largest river in California (Fig. 1). The maximum watershed elevation is approximately 1800 m, but a majority of the watershed area is below 1200 m. Average annual precipitation in Redding, California, varies from 500 mm to 1600 mm, with a mean annual precipitation of about 1000 mm. The climate is Mediterranean and most precipitation falls as rainfall from November to March (77% of the mean annual precipitation), with little or none occurring during the months of May through September. Ambient air temperatures are typically lowest in January (average minimum 3 °C to average maximum 14 °C) and highest in July (average minimum 20 °C to average maximum 38 °C).

"Clear Creek" used in this study refers to the portion of the creek downstream of Whiskeytown Dam. Clear Creek, starting at Whiskeytown Dam at river km 30, flows south before flowing east approximately 14 km to the Sacramento River (Fig. 1). The drainage area between Whiskeytown Dam and the confluence with the Sacramento River is 127 km^2. Separated at the Clear Creek Road Bridge, the upper (almost 16 km) and lower (approximately 14 km) reaches of the creek are geologically distinct (Giovannetti and Brown, 2008). The upper reach flows south from Whiskeytown Reservoir. The stream bedrock in the upper reach is composed primarily of Paleozoic to Mesozoic igneous, metasedimentary, and metamorphic rocks that are largely resistant to erosion. The stream is more constrained by canyon walls and a bedrock channel and has a higher gradient, less spawning gravels, and greater pool depths than the lower portion of Clear Creek. The lower reach flows in an easterly direction to the Sacramento River. The stream bedrock in the lower reach is composed of sedimentary rocks that are much less resistant to erosion. The stream meanders through a less constrained alluvial channel, and has a lower gradient, more spawning gravels, and fewer deep pools (Giovannetti and Brown, 2008).

Construction of the earthfill, 80 m tall Whiskeytown Dam began in 1959 and was completed in 1963. Whiskeytown Reservoir has an approximate capacity of 300 million m^3 with a surface area of 14,000 km^2. The reservoir, part of the federal Central Valley Project in California, is operated by the U.S. Bureau of Reclamation for flood control, irrigation water, electricity generation, fish and wildlife, and recreation. The majority of the reservoir water (73% of the annual inflow on average) comes from Lewiston Reservoir supplied by the Trinity River downstream of Trinity Reservoir. Whiskeytown Dam entirely blocks fish from accessing the upper stream and has dramatically altered hydrology downstream of the dam. Furthermore, the reservoir, acting as a sediment trap, has starved lower Clear Creek of gravel, resulting in a substantial reduction of spawning habitat in lower Clear Creek (McBain et al., 2001).

A large portion of the Whiskeytown Reservoir water (85% of the annual outflow on average) leaves through the Spring Creek Tunnel, which has a discharge capacity of 108 cubic meters per second (cms) equivalent to 3800 cubic feet per second (cfs), to Keswick Reservoir on the upper Sacramento River (Fig. 1), whereas a small portion of the reservoir water (15%) discharges to Clear Creek. There are two intakes at Whiskeytown Dam that discharge reservoir water to Clear Creek. The upper intake at the elevation of 340 m has a discharge capacity of 17 cms, while the lower intake at the elevation of 301 m has a discharge capacity of 35 cms.

Clear Creek currently supports spring-run Chinook salmon (spring- run), fall-run Chinook salmon (fall-run), and late fall-run Chinook salmon (late fall-run) and steelhead trout (steelhead). Spring-run and steelhead have been listed as threatened under the federal Endangered Species Act. Although the life history of

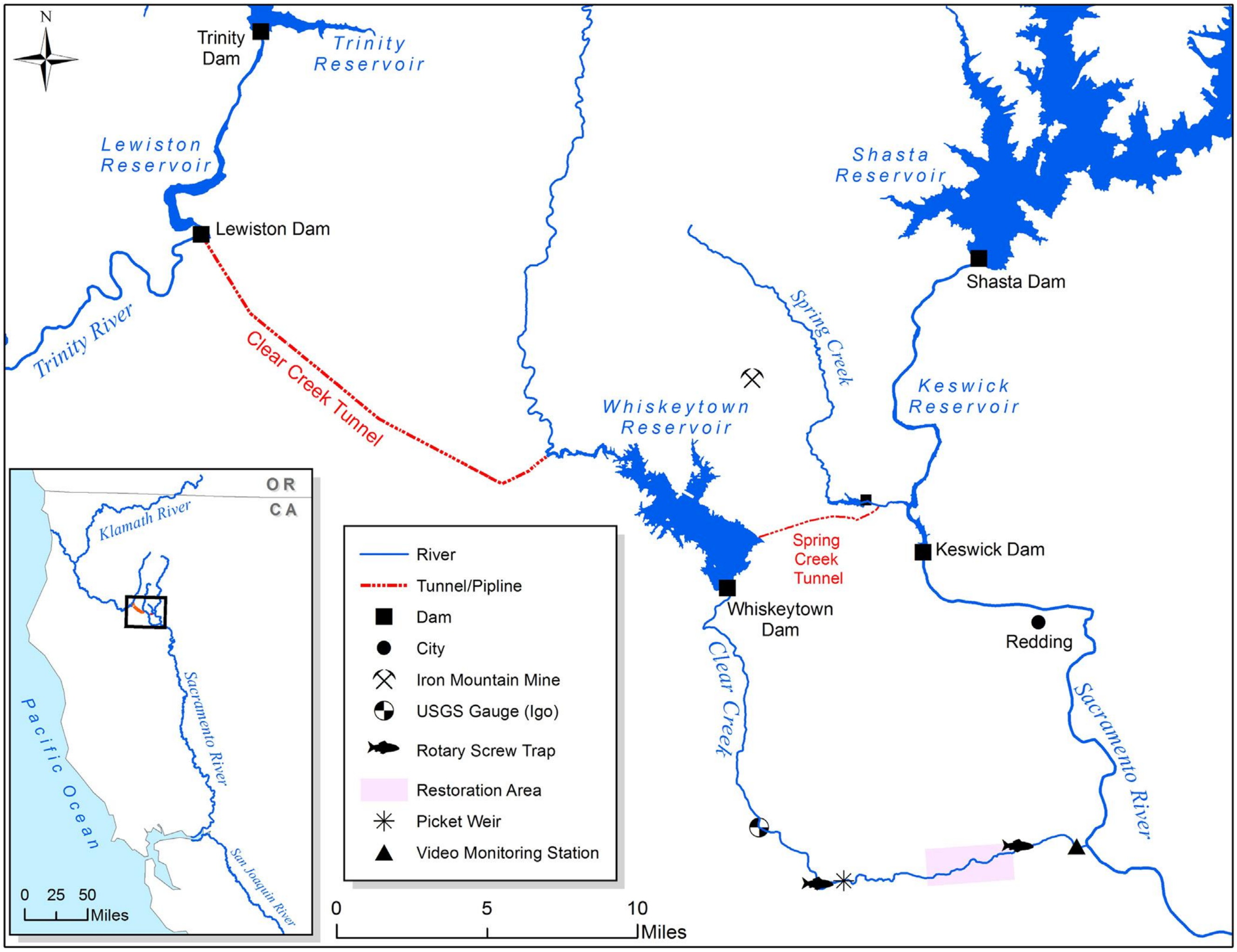

Fig. 1. Map showing Clear Creek, Whiskeytown Reservoir, and vicinity.

salmonids is unique for each of these species, they spend about one quarter to one half of their lifetime—including the most sensitive life stages—in freshwater. Spring-run adults begin to enter Clear Creek in late April and hold there over the summer (May through September). Although their peak immigration into Clear Creek occurs from May through June, adult monitoring data indicate that they may move up and down stream. Spawning begins in early September and ends in late October, with hatching and emergence occurring in November and December (Earley et al., 2013; Giovannetti and Brown, 2013). The majority of spring-run juveniles outmigrating from Clear Creek are fry as opposed to smolts (Earley et al., 2013), although some may rear in Clear Creek for a full year before outmigration. Migration occurs from November through February, with peak migration in December. Fall-run adults immigrate into Clear Creek from September through November and spawn from October through December (Williams, 2006). The majority of the outmigrating fall-run juveniles are fry and migration occurs from December through March (Earley et al., 2013). We did not analyze late fall-run as their population size is much smaller than the other two Chinook salmon races in Clear Creek. Adult steelhead enter freshwater in fall and winter (September to February) and spawn in winter and early spring (December to April) (Giovannetti et al., 2013). The majority of the steelhead juveniles outmigrate from Clear Creek as fry between February and May (Earley et al., 2013), although some of them may rear in Clear Creek for one year or two before outmigration as smolts. Spring-run spawn in the upper reach of Clear Creek, fall-run spawn in the lower reach, and steelhead spawn in both reaches.

3. Methods

3.1. Environmental data

We obtained and compiled a variety of environmental data to use in this study, including streamflow, reservoir release, water temperature, air temperature, and precipitation (Table 1). In all cases, data were checked to assure data quality. Any records that showed apparent recording errors (*e.g.*, spikes on streamflow, temperature, or other variables) or were marked as “missing” were excluded from use in the study.

3.2. Fish data

We obtained both adult and juvenile fish monitoring data for spring- run, fall-run, and steelhead in Clear Creek (Table 2). The adult spring-run index in Clear Creek was determined by snorkel survey in August for each year of the study. Beginning in 2003 to reserve the upper reach for use of spring-run adults, a picket-fence weir (see Fig. 1 for location) was installed in August each year when immigration of spring-run adults completed. This picket-fence weir prevented fall-run adults from accessing the upper reach where spring-run adults were spawning. We used the spring-run adult

Table 1
Environmental datasets and their sources.

Dataset	Source
Clear Creek Streamflow @Igo (cms)	USGS 11372000; http://waterdata.usgs.gov/ca/nwis
Inflow to Whiskeytown Reservoir (cms)	Whiskeytown Dam; http://cdec.water.ca.gov
Reservoir Release to Clear Creek or Spring Creek Tunnel (cms)	Whiskeytown Dam; http://cdec.water.ca.gov
Reservoir Temperature (°C)	U.S. Bureau of Reclamation
Clear Creek stream temperature @Igo (°C)	IGO; http://cdec.water.ca.gov
Air temperature @Redding (°C)	RED; http://cdec.water.ca.gov
Precipitation @Redding (mm)	California Climate Data Archive; http://www.calclim.dri.edu/ccda/data.html
Water Diversion from Lewiston Reservoir to Whiskeytown Reservoir (cms)	JCR; http://cdec.water.ca.gov

USGS = U.S. Geological Survey. RED = Redding. JCR = Judge Carr Powerhouse.

Table 2
Fish datasets and their sources.

Dataset	Adult Fish Data Source	Juvenile Fish Data Source
Spring-run Chinook salmon	U.S. Fish and Wildlife Service; http://www.calfish.org	U.S. Fish and Wildlife Service
Fall-run Chinook salmon	California Department of Fish and Wildlife; http://www.calfish.org	
Steelhead	U.S. Fish and Wildlife Service	

population index data from 2003 to 2013. The annual adult fall-run abundance in Clear Creek was estimated from carcass surveys conducted weekly from October through December. Although data for adult fall-run abundance were available as far back as 1953, we did not include the data prior to 1988 because there were 12 years of missing data between 1953 and 1987. The number of adult steelhead in Clear Creek has been estimated through redd surveys since 2003 (Giovannetti et al., 2013). Kayak-based redd surveys are conducted every two weeks from approximately mid-December through early April. The annual juvenile abundance of each salmonid species in Clear Creek is estimated from the number of fish caught by two rotary screw traps (RSTs). The upstream RST at rkm 13.5 has been operated since 2003 to capture spring-run juveniles, while the downstream RST at rkm 2.7 has been operated since 1998 to capture fall-run and steelhead juveniles. The total number of juvenile salmonids passing downstream in a given unit of time is calculated from the number of fish caught by the RST and the RST efficiency, which is determined by the mark-recapture method (Earley et al., 2013). We used juvenile monitoring data from 2003 to 2012 for spring-run and steelhead (adult steelhead monitoring data were not available until 2003) and from 2001 to 2012 for fall-run because of the removal of Saeltzer Dam in 2000, which was located about 10 miles downstream of Whiskeytown Dam.

3.3. Analyses of pre- and post-project stream flows

We analyzed stream flows in Clear Creek by dividing the flow data into three time periods relative to dam construction: Period 1—the pre-project period (water years 1941 to 1958),[1] Period 2—the first post-project period (water years 1965–1994), and Period 3—the second post-project period (water years 1995–2013). We consider the pre-project flows as “natural” flows in Clear Creek even though many activities, including gold mining, occurred as early as the 1840s. A better understanding of the pre- project flow regime, under which aquatic species have evolved life history strategies, provides a basis for instream flow development and stream restoration. We divided the annual pre-project hydrograph into three blocks based on magnitude and timing of flow. We excluded the time period of 1959–1964 due to apparent interferences from dam construction activities. We separated the post-project time into two periods because flows were generally increased since 1995 to improve Chinook salmon and steelhead populations in Clear Creek.

We assessed flow changes in Clear Creek by comparing the pre-project flows to the post-project period flows. Hydrologic attributes used in comparison included flood flows, pulse flows, and mean monthly flows. Flood flows refer to peak flows with magnitudes near or above stream banks and occur in 1.5 or more years. Pulse flows refer to daily high flows that rise above the 75th percentile of all daily values within the spring time period (March through May). Mean monthly flows refer to the daily flow averaged on a monthly basis. Base flows refer to those flows occurring between flood flows or pulse flows, caused by the receding limb of flood or pulse flows and contributions of groundwater recharge. Differences in flow between pre- and post-project periods may be caused by factors including reservoir operations and changes in precipitation. For example, lower precipitation in the post-project period compared to the pre-project period may result in lower stream flows in Clear Creek. We therefore compared annual precipitation (water year) in the pre-project period to those in the post-project periods.

We analyzed these data using the indicator of hydrologic alteration (IHA) software (http://www.conservationgateway.org) and Minitab (Minitab Inc., State College, PA). These analyses were conducted using the default nonparametric option analyses built into the IHA. In the IHA analysis, duration is defined as the length of time from the beginning of the rise above a base flow, until the time when flow returns to the base flow. We compared the data between the pre- and post-project time periods using the nonparametric Mann–Whitney U test whenever appropriate.

3.4. Analyses of water temperature and reservoir release

We evaluated water temperature impairments by comparing observed temperatures to water temperature criteria for each life stage of salmonids in Clear Creek. The comparison was focused on the second post-project period, as there were no water temperature data available for the pre-project or the first post-project period. We used the water temperature criteria recommended for salmonids by the U.S. Environmental Protection Agency (2003). The 7-day average of the daily maximum (7DADM) temperature is the moving average of daily maximum temperatures over a seven-day consecutive period and reflects an average of maximum temperatures that fish are exposed to over a week-long period. The 7DADM describes the maximum temperature in a stream, but it is not overly influenced by the maximum temperature of a single day. Since this metric is oriented to daily maximum temperatures, it can be used to protect against acute effects, such as lethality and migration blockage conditions where high water temperatures (e.g., above 20 °C) may block upstream migration of salmonid adults. This metric can also be used to protect against sub-lethal or chronic effects (*e.g.*, temperature effects on growth, disease, smoltification, and competition) (U.S. Environmental Protection Agency, 2003). The 7DADM is commonly referred to as the maximum weekly maximum temperature (MWMT) in the literature.

In a stream where there are coexisting species, it is necessary to meet the most conservative physiological and habitat need of

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[1] The term “water year” is defined as the 12-month period from October 1 for any given year through September 30 of the following year. The water year is designated by the calendar year in which it ends and which includes 9 of the 12 months. Thus, the year ending September 30, 1999 is called the 1̈999ẅater year.

the species. There are three anadromous salmonid species in Clear Creek: spring-run, fall-run, and steelhead. They experience the following life stages in Clear Creek: adult migration, adult holding (spring-run only), spawning, egg incubation, fry emergence, and juvenile rearing and outmigration. Due to timing differences in the life history of the three species, the water temperature criterion of 13 °C for spawning, egg incubation, and fry emergence needs to be maintained for steelhead from January through May and for spring-run and fall-run from September through December, while maintained at 16 °C for spring-run and steelhead juvenile rearing or spring-run adult holding from June through August. These water temperature criteria were recommended for salmonids by U.S. Environmental Protection Agency (2003).

We computed the number of days when the observed water temperature exceeded water temperature criteria at five exceedance levels: 0.25, 0.5, 1, 2, and 3 °C. The U.S. Environmental Protection Agency (2003) indicated that an increase on the order of 0.25 °C for all sources cumulatively (at the point of maximum impact) above fully protective numeric criteria would not impair designated uses and, therefore, might be regarded as *de minimis*. We used 0.25 °C as a *de minimis* temperature increase above the water temperature criteria. The *de minimis* increase allowance serves as a way of accounting for monitoring measurement error and tolerating negligible human impacts. We used other exceedance levels to assess the severity of potential water temperature impacts on anadromous salmonid species in Clear Creek.

Stream temperature impairment may be reduced by restoring gravel bars and riparian vegetation and releasing cold water from an upstream reservoir. While restoration of riparian vegetation, where appropriate, could serve as a long-term goal, reservoir cold water release may be used as an effective means to meet the water temperature criteria in the short term. We hypothesize that water temperature at the USGS Igo station (rkm 18) in Clear Creek is correlated to the quantity of water released from Whiskeytown Reservoir and ambient weather conditions. Important factors of weather conditions that affect stream temperature include air temperature and solar radiation (Caissie et al., 2001; Neumann et al., 2003; Morrill et al., 2005; Sahoo et al., 2009 Because solar radiation data in the study area were missing or appeared erroneous, we opted for using air temperature data only. We therefore used the daily data for water temperature, reservoir flow release, and air temperature to develop a regression model for water temperature prediction. Use of the regression model allows for estimating the quantity of reservoir release, given the water temperature criterion and air temperature. The multiple linear regression was used to fit a set of data with the following equation:

$$\hat{T}_w = a_0 + a_1 Q_r + a_2 T_a \quad (1)$$

where $\hat{T}_w$ = predicted daily water temperature in Clear Creek (7DADM, °C); Q_r = daily reservoir release from Whiskeytown Reservoir (cms); T_a = daily average air temperature (°C); and a_0, a_1, a_2 = coefficients.

The regression model provides a practical relationship between water temperature and reservoir release and air temperature. Its direct application is the estimation of additional water required in Clear Creek to reduce water temperature to a specified limit (*i.e.*, a water temperature criterion).

Rearranging the regression model (Eq. (1)) to solve for reservoir release ($\hat{Q}_r$) gives

$$\hat{Q}_r = \frac{T_{w(target)} - a_0 - a_2 T_a}{a_1} \quad (2)$$

where $T_{w(target)}$ = specified water temperature target. Since there is a wide range of T_a, its percentile values were computed and used to estimate the reservoir release to meet a specified water temperature target. The amount of reservoir release from the percentile-based method does not represent the actual reservoir release for a specific day, but can serve as a guideline for categorizing reservoir releases to meet the water temperature criteria under a set of pre-defined air temperatures. In reality, one would expect air temperatures to occur randomly within the range.

An empirically-developed multiple linear regression model may fit the data used to estimate the regression coefficients very well, but it is unknown if the model predicts new data well. We used the water temperature, reservoir release, and air temperature data from 1995 through 2013 and divided them into two datasets: one set for model development excluding the 2008 data and the other set for model validation with the 2008 data only. By validating the model with randomly selected 2008 observations, which were not used in fitting the regression, we were able to assess the ability of the model to predict future events.

Reservoir water temperature is expected to affect the temperature of released water, which in turn would impact the downstream temperature of Clear Creek. However, because the most complete reservoir temperature dataset was limited to monthly (rather than daily) measurements at the elevation of 343 m from 2000 to 2009, we were unable to include reservoir temperature in the regression model.

Any records of the data showing zero reservoir release were not included in developing the regression model. Any records of data that showed the ratio of the Whiskeytown Reservoir release to streamflow at Igo less than 0.8 or greater than 1.2 were also excluded to minimize the impact of high depletions or other flow sources than the reservoir release. Any data with daily precipitation >5 mm (0.2 in.) were not included to avoid potential influence of rainfall-generated runoff (this only excluded a very small portion (3.2%) of the entire data set). We are only interested in the time period of May through October with high water temperature but little or no rainfall, both of which are likely to occur in these months.

3.5. Assessing the impact of flow and water temperature on salmonid abundance in Clear Creek

We evaluated how adult or juvenile abundances of salmonids in Clear Creek respond to flow and water temperature. We hypothesized that juvenile salmon would demonstrate demographic responses to flow and water temperature. This hypothesis was tested by modeling how independent variables (i.e., flow magnitude or water temperature) affected the abundances of adults or juveniles in Clear Creek. We used an information theoretic approach (*i.e.*, Akaike's information criterion (AIC)) to evaluate the weight of evidence for streamflow or water temperature. The AIC corrected ($\mathrm{AIC_c}$) for small sample size was calculated for each candidate model. The difference ($\Delta\mathrm{AIC_c}$) in $\mathrm{AIC_c}$ values between each candidate model and the best model was calculated, and models with a $\Delta\mathrm{AIC_c}$ value <2 were considered to have similar support in the data (Burnham and Anderson, 2002). Model weights ($\mathrm{AIC_c}$ Weight) and evidence ratios were also calculated. Model weights are interpreted as the probability that a particular model is the best fit to the data relative to all other models being considered. Evidence ratios <3 indicate the level of support for two or more competing models based on AICc weights (Arthaud et al., 2010). Thus, using $\Delta\mathrm{AIC_c}$ and evidence ratios, it is possible to evaluate the relative weight of evidence for the effects of streamflow or water temperature on the abundance of salmonids.

4. Results

4.1. Pre-project flow in Clear Creek

Pre-project flows in Clear Creek for three broad hydrologic year types (i.e., wet, normal, and dry) are presented in Fig. 2. Each of

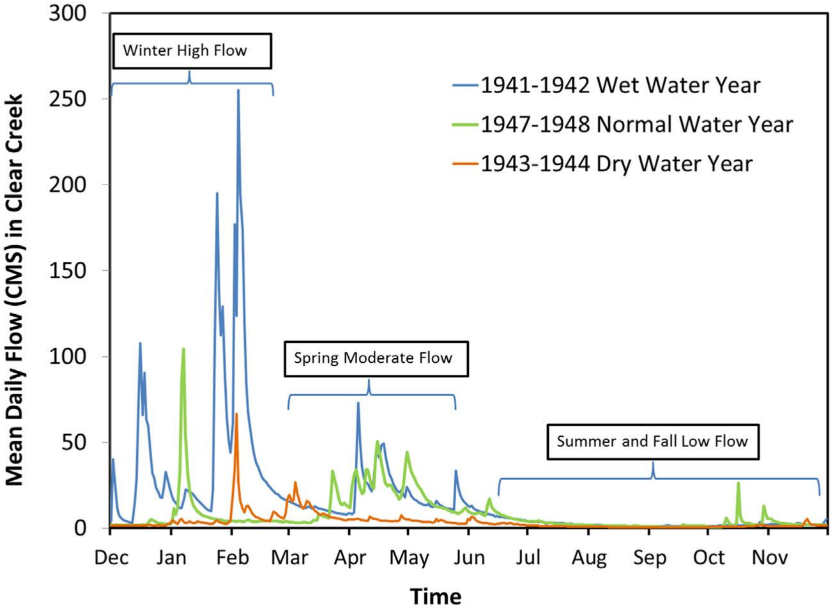

Fig. 2. Pre-project Clear Creek annual hydrographs representing a wet water year (1942), normal water year (1948), and dry water year (1944).

these annual pre-project hydrographs can be partitioned into three blocks based on the magnitude and timing of flow: winter high flow, spring moderate flow, and summer and fall low flow (Fig. 2). These are key hydrologic components that drive ecologic, geomorphic, and biological processes in a river system under hydroclimatic conditions in northern California.

4.1.1. *Winter high flow*

Winter high flows typically occur from December through February (Fig. 2), with the largest flows occurring from mid-January to mid-February (Fig. 3). We divided the winter high flow into two categories: winter flood flow and base flow. Winter flood flows refer to peak flows occurring from December through February. The low elevation and relative imperviousness of the watershed, combined with periodic high intensity rainstorms, resulted in an extremely flashy streamflow response to rainfall events. These floods were of large magnitude and short duration relative to the small watershed area in Clear Creek. Generally, wetter years produced larger peak flows than dry years. Dry years typically had instantaneous peak flows between 100 cms and 200 cms, while wetter years had instantaneous peak flows between 300 cms and 500 cms, with the highest instantaneous peak flow reaching nearly 700 cms in 1956.

The IHA results indicated that the median 1.5-year winter flood flow in Clear Creek during the pre-project period was 174 cms and most likely occurred in January or February. These flood flows were typically of extended duration (40 days) and had a high rising rate (31 cms/day) and low falling rate (7 cms/day). These storm-induced flood flows would cause the channel to avulse or migrate, scour streambed, move and redeposit alluvial sediments, form floodplains, and erode patches of riparian vegetation (Trush et al., 2000). Winter base flows refer to those flows occurring between individual winter storm events, caused by the receding limb of winter flood flows and contributions of groundwater recharge. Winter base flows generally occurred over the same period as winter storm events, but could extend into the spring snowmelt flow period. Winter base flows ranged from 5 to 10 cms during drier years to 30–60 cms during wetter years (Fig. 3).

4.1.2. *Spring moderate flow*

Spring moderate flows occur from March through May (Fig. 2), but the recession flow could extend into June (Fig. 3). We divided the spring moderate flow into two categories: Spring pulse flow and base flow. Spring pulse flows on Clear Creek occurred in March and April but sometimes in May (Fig. 2). The pulse flows were typically <40 cms but occasionally exceeded 100 cms in some years. The highest snowmelt pulse flows seemed to occur in early April (Fig. 3). The IHA results indicated that the median spring pulse flow from March through May was 22.6 cms with a duration of 12 days. Spring base flows on Clear Creek remained relatively high in March and gradually receded from April into June (Fig. 3). The base flow in March was typically between 15 and 20 cms.

4.1.3. *Summer and fall low flow*

Summer and fall low flows began at the end of the snowmelt flow in June or July, and ended in November with the arrival of the first rainfall event. These low flows were typically <2 cms during wetter water years and <1 cms in drier years (Fig. 3). The granitic and metamorphic rocks that comprise the upper Clear Creek watershed have low permeability, so winter precipitation runs off relatively rapidly, resulting in low flows in summer and fall. These low flows sustained aquatic habitat through the summer and fall dry season, providing habitat for aquatic organisms, maintaining suitable water quality, and providing water for terrestrial animals.

4.2. *Flow alteration from water operation*

We compared annual precipitation in the pre-project period to that in post-project periods. Statistical results (one-way ANOVA) indicated that precipitation in the three periods of 1941–1958, 1965–1994, and 1995–2013 were not significantly different ($p = 0.283$).

4.2.1. *Changes in flood flows*

IHA results indicate that post-project flood flows in Clear Creek have been reduced substantially. The 1.5–10-year flood flows in Clear Creek are presented in Table 3. The 1-day average 1.5-year flood flows decreased from 174 cms in the pre-project period to 29 cms in the first post-project period (decreased by 83%) and to 42 cms in the second post-project period (decreased by 76%). The magnitudes of 2-, 5-, and 10-year floods also decreased substantially (Table 3). The frequency of the pre-project 1.5-year flood

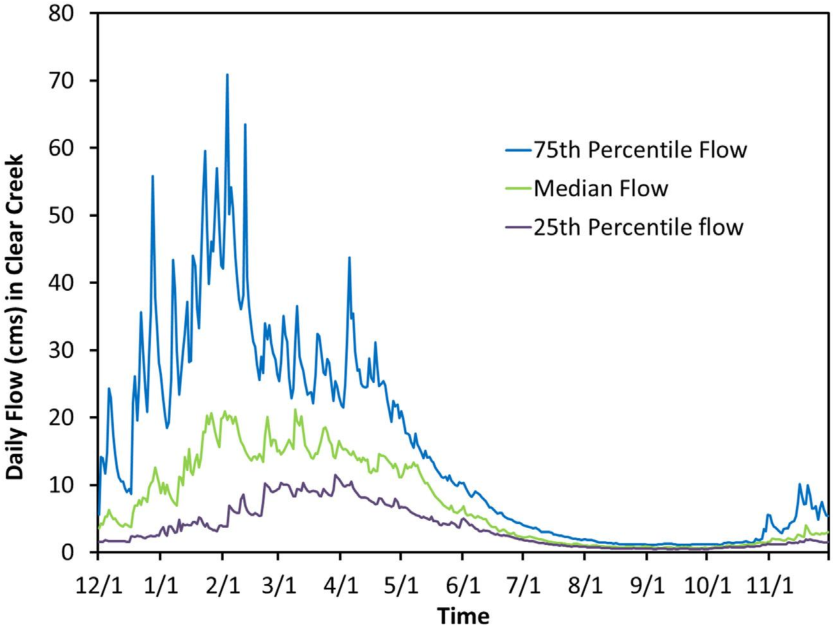

Fig. 3. 75th percentile, median, and 25th percentile daily flows in Clear Creek during the pre-project period of 1941–1958.

Table 3
Changes in flood magnitude (cms) for 1.5–10-year floods in Clear Creek.

Period	1.5-Year Flood	2-Year Flood	5-Year Flood	10-Year Flood
Period 1 (1941–1958)	174	255	396	428
Period 2 (1965–1994)	29	59	119	197
Period 3 (1995–2013)	42	68	120	237
Percent Reduction (P1 and P2)	83%	77%	70%	54%
Percent Reduction (P1 and P3)	76%	73%	70%	45%

flows, which are considered bankfull or floodplain inundation flows in Clear Creek, was reduced to once every 5–10 years in the post-project periods.

The duration of the 1.5-year flood flows decreased from 40 days in the pre-project period to 9 days in the post-project period, *i.e.*, a 78% reduction. The flood flow rise rates from the pre-project period to the second post-project period increased by 26%, whereas the fall rates increased by 130%.

While a few small tributaries to Clear Creek downstream of the dam contributed to short-duration flood flows, the small drainage area limits tributary flood flows to less than 100 cms. Flood flows >100 cms generally resulted from uncontrolled spillway releases from Whiskeytown Reservoir, as happened in water years 1983 (425 cms), 1997 (243 cms), and 1998 (231 cms).

4.2.2. *Changes in spring pulse flows*

Spring pulse flows provide cues for upstream and downstream migrations of salmonids and influence sediment transport. The magnitude of median spring pulse flows in Clear Creek was reduced by 75% from the pre-project period to the first post-project period and by 43% from the pre-project period to the second post-project period.

4.2.3. *Changes in monthly flows*

Median monthly flows in Clear Creek in the months of January through May decreased by 77–82% from the pre-project period (Period 1) to the first post-project period (Period 2), with the highest decrease in April, while the flow reduction was less severe in June (61%) and December (42%). Median monthly flows in Clear Creek decreased by 27–53% from Period 1 to the second post-project period (Period 3) in the months of December through May, while increased by 12–426% in the months of June through November. Decreases or increases in monthly flows between Period 1 and Period 2 or Period 3 are statistically significant except in June (Fig. 4). Median monthly flows increased for all the months from Period 2 to Period 3 by 67% (August) to 287% (October).

4.2.4. *Changes in daily flows*

Median daily flows in the months of January through May decreased by 67–87% from the pre-project period (Period 1) to the first post-project period (Period 2), and decreased by nearly 0–64% from Period 1 to the second post-project period (Period 3) (Fig. 5). Median daily flows increased for all the months from Period 2 to Period 3.

4.3. *Water temperature*

4.3.1. *Water temperature in Clear Creek*

The highest water temperatures (7DADM) in Clear Creek from 1996 to 2013 occurred in July and the second-highest temperatures occurred in August; the lowest water temperatures occurred in January and February (Fig. 6). Water temperatures exceeded the 16 °C criterion for spring-run and steelhead juvenile rearing or spring-run adult holding in July and August, and the 13 °C criterion for steelhead egg incubation or fry emergence in May and for spring-run spawning, egg incubation, or fry emergence in September and October. We focus on the water temperature analysis for the months of May through October when water temperatures may exceed water temperature criteria for salmonids. Monthly water temperatures in Clear Creek occur in decreasing order according to: July > August > June ≈ September > May ≈ October (Fig. 6). The

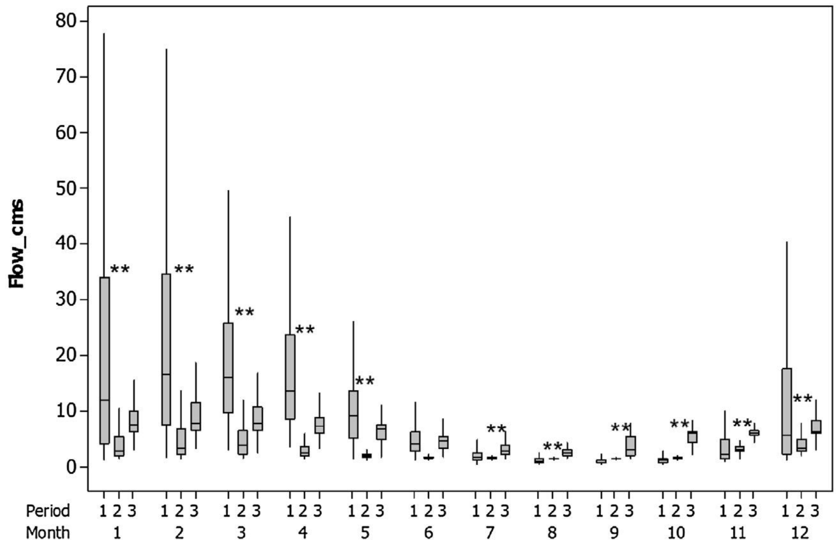

Fig. 4. Monthly stream flows in Clear Creek in three time periods: Period 1 represents the pre-project period (1941–1958), Period 2 the first post-project period (1965–1994), and Period 3 the second post-project period (1995–2013). Statistically significant differences between Period 1 and Period 3 are indicated by asterisks (**, $p < 0.01$). Key to boxplots: horizontal line, median; box, 25th (Q1) and 75th (Q3) percentiles; whiskers, lower and upper limits. The lower limit = Q1 − 1.5 (Q3 − Q1). The upper limit = Q3 + 1.5 (Q3 − Q1). Month 1 = January.

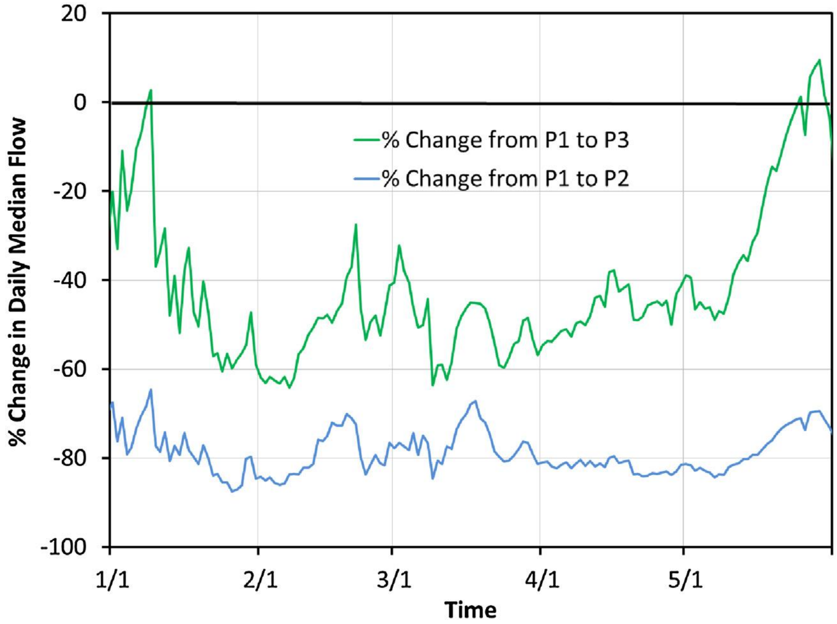

Fig. 5. Percent change in median daily flows in Clear Creek from the pre-project period (P1: 1941–1958) to the first post-project period (P2: 1965–1994) or the second post-project period (P3: 1995–2013).

occurrence of temperatures showed somewhat similar distribution patterns for June and September, and for May and October (Fig. 6). On average, there were 100, 78, 51, 16, and 2 days per year exceeding the water temperature criteria by 0.25, 0.5, 1, 2, and 3 °C, respectively. The number of days of exceedance by month showed the following decreasing order: September $\gg$ May > October $\approx$ July > June $\approx$ August. The observed water temperatures exceeded the criteria (0.25 °C above the criteria) for 30 days in September, 20 days in May, 17 days in July, and 16 days in October.

4.3.2. Water temperature in Whiskeytown reservoir

Water temperature in Whiskeytown Reservoir was periodically measured at various depths from surface to bottom. We summarized reservoir temperature data at two depths: elevation at 340 m at the upper intake location and 301 m at the lower intake location (Fig. 7). The monthly reservoir temperature showed a similar pattern between the two water depths: lowest in February for both locations, but highest in August at the elevation 340 m and in September at the elevation 301 m. Differences in reservoir temperature between these two depths started to increase in April (a difference of 0.6 °C), reached the highest in July and August (a difference of 1.7 °C), and decreased starting September (a difference of 0.8 °C).

4.3.3. Water temperature model

We developed a multiple regression model for estimating the quantity of reservoir release to meet water temperature require-

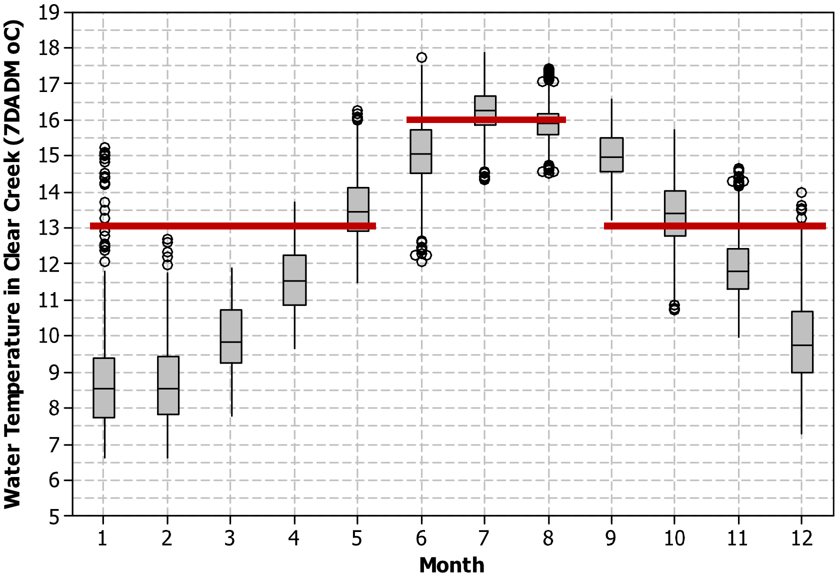

Fig. 6. Box plot of daily water temperature (7DADM °C) at Igo in Clear Creek from 1996 to 2013. Red lines represent water temperature criteria for salmonids: 13 °C for spawning, egg incubation, and fry emergence and 16 °C for juvenile rearing. Key to boxplots: horizontal line, median; box, 25th (Q1) and 75th (Q3) percentiles; whiskers, lower and upper limits; circles, values beyond the lower or upper limits. The lower limit = Q1 − 1.5 (Q3 − Q1). The upper limit = Q3 + 1.5 (Q3 − Q1). Month 1 = January. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

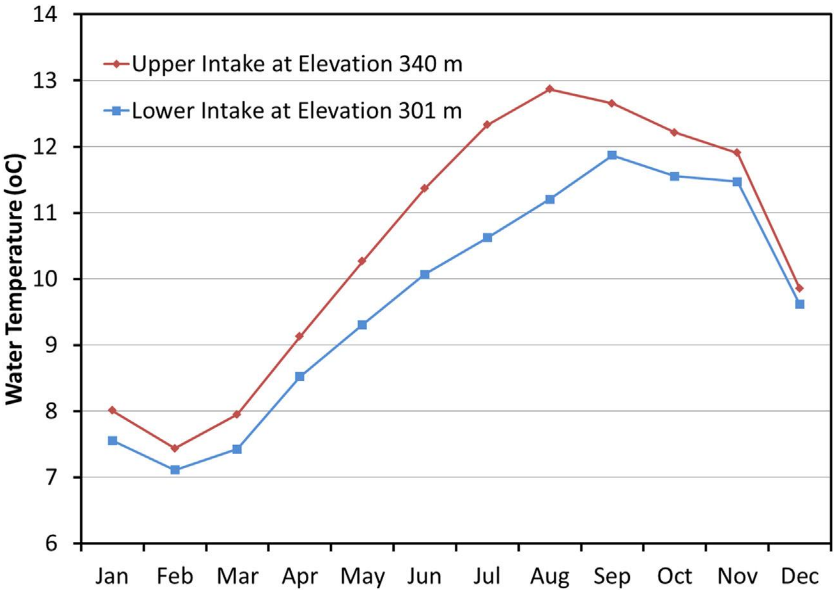

Fig. 7. Mean monthly Whiskeytown Reservoir temperature at two water depths from 2000 to 2009.

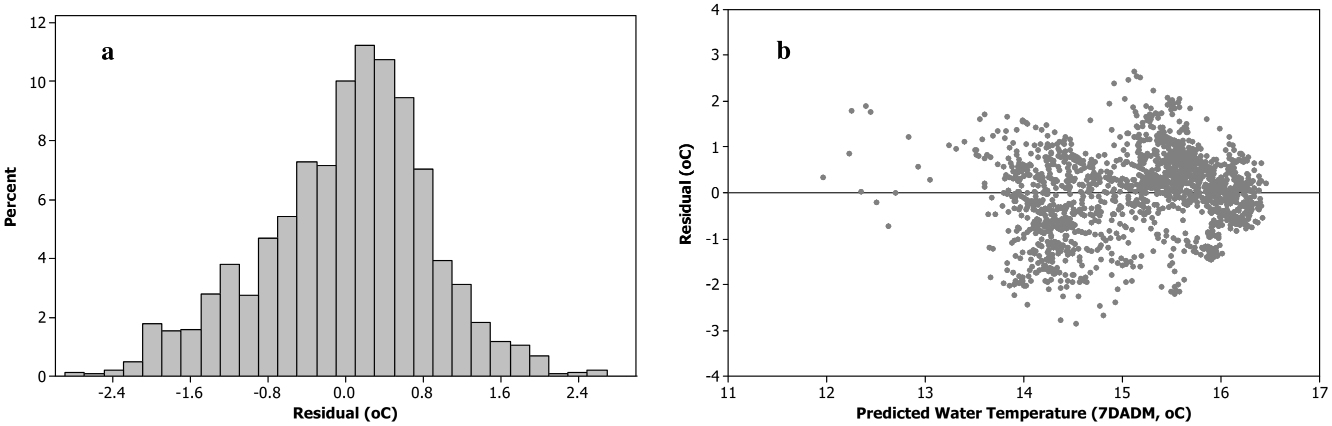

Fig. 8. Residual plots for water temperature predictions. (a) Histogram. (b) Scatter plot.

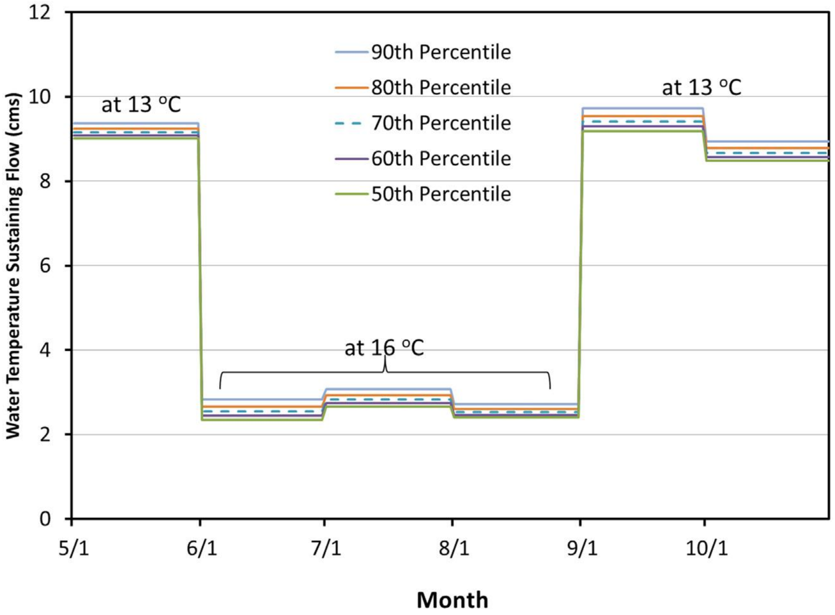

Fig. 9. Estimated reservoir release required for sustaining adequate water temperatures in Clear Creek during the six months of May through October when water release rates from Whiskeytown Reservoir are close to stream flows at Igo.

ments at Igo for a given water temperature criterion and air temperature. The statistical results indicate that water temperature at Igo is significantly correlated to reservoir release and air temperature ($r^2 = 0.53$, $p < 0.01$). The regression coefficients of Eq. (2) are $a_0 = 15.73$, $a_1 = -0.419$, and $a_2 = 0.0478$. We evaluated the regression model by examining the normality and random distribution of residuals. Linear regression theory assumes residuals are normally distributed and symmetric about the mean. The histogram of the residuals shows that the residuals appear to be normally distributed and centered on zero (Fig. 8a). There is no curvature and variance in residuals, but it appears to decrease at higher water temperatures (Fig. 8b). While the regression model performs well for water temperature prediction, the model tends to overestimate lower water temperatures and underestimate higher ones. We validated the model using observations not used in fitting the regression to assess the ability of the model to predict future events. The model predicts the 2008 data very well ($r^2 = 0.83$, $p < 0.01$).

We used Eq. (2) to estimate the quantity of reservoir release to meet water temperature criteria at Igo (Fig. 9). From May through October, Whiskeytown Reservoir release dictates streamflow at Igo in Clear Creek. The estimated reservoir release in cms is the percentile flow that considers mean daily air temperature and water temperature criteria. For example, the estimated release of 2.8 cms from Whiskeytown Reservoir in June would make 90% of water temperatures at Igo lower than 16 °C, while the estimated reservoir release of 9.7 cms in September would make 90% of water temperatures at Igo lower than 13 °C (Fig. 9). The magnitude of estimated reservoir releases as shown in Fig. 9 is similar to the average streamflow at Igo for the second post- project period (1995–2013) in July, August, and December, but higher from September to November and from January to June.

4.4. Impact of flow and water temperature on salmonid abundance in Clear Creek

Adult spring-run abundance in Clear Creek increased from 2001 to 2008; it decreased after 2008 and plunged to a low level in 2010 and 2011, after which it increased again in 2012 (Fig. 10). Adult fall-run abundance fluctuated widely, with an average of 6571 adults from 1988 to 2013 (Fig. 10). Adult steelhead abundance (measured as redds) increased from 2003 to 2009 but decreased from 2010 to 2012 (Fig. 10). Juvenile spring-run abundance in Clear Creek showed a dramatic decrease from 2008 to 2010, while juvenile fall-run abundance varied substantially from year to year. Juvenile steelhead abundance appeared to be stable from 2004 to 2012 (Fig. 11).

Model selection based on ΔAIC_c and evidence ratio revealed that the average water temperature in June had the best support for predicting the adult spring-run abundance (Table 4). The model showed good overall fit to the data ($r^2 = 0.48$, $p = 0.03$). The slope in the model was negative, indicating that the adult spring-run abundance in Clear Creek decreased as water temperature increased. The average water temperature in October had the best support for predicting the juvenile spring-run abundance, which decreased with increasing water temperature ($r^2 = 0.50$, $p = 0.02$). The average September streamflow in Clear Creek had the best support for predicting the adult fall-run abundance (Table 4), which increased with increasing streamflow. The model showed good overall fit to the data ($r^2 = 0.30$, $p < 0.01$). The average November water temperature showed the best support for predicting the juvenile fall-run abundance ($r^2 = 0.35$, $p = 0.04$), decreasing with increasing water temperature. Average water temperatures in January, December, or August showed better support for predicting the adult steelhead abundance than those in September, October, or November (Table 4), which increased with decreasing water temperature. The average water temperature in June had the best support for predicting the juvenile steelhead abundance ($r^2 = 0.784$, $p < 0.01$).

5. Discussion and conclusion

Streamflow and water temperature are major determinants of energetics and metabolism of stream fishes with consequent strong influences on their survival, growth, and fitness. It is clear that both flow and water temperature have impacted the abundance of both adult and juvenile salmonids in Clear Creek.

5.1. Potential effects of streamflow on salmonids

Streamflow has been deemed a “master variable” because it strongly influences fish and the food web, and it has substantial

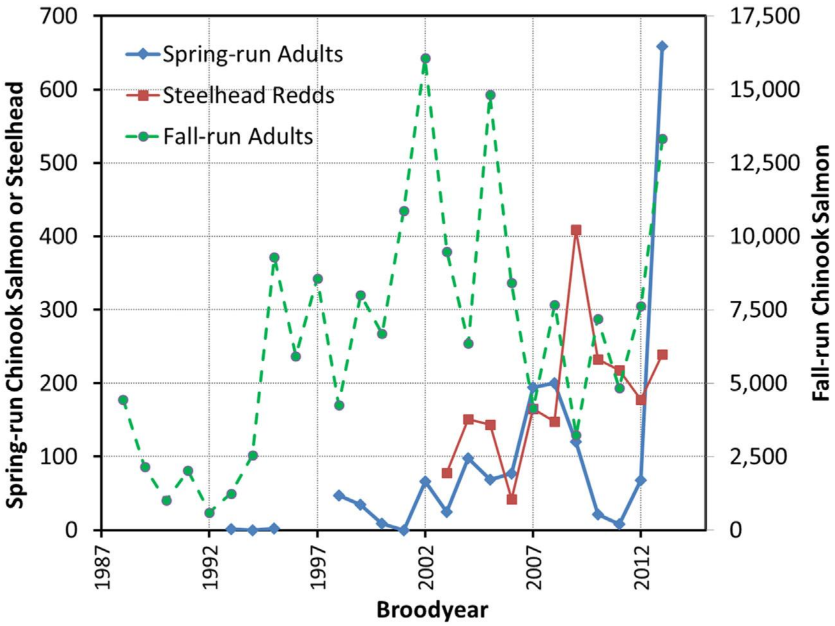

Fig. 10. Annual abundance of adult spring-run and fall-run Chinook salmon and steelhead in Clear Creek.

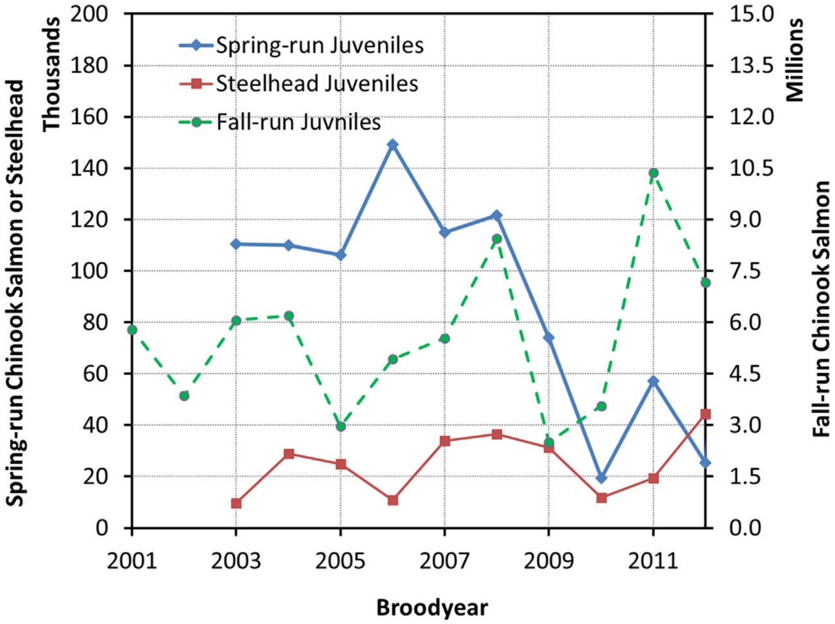

Fig. 11. Annual abundance of juvenile spring-run and fall-run Chinook salmon and steelhead in Clear Creek.

effects on spawning and rearing habitat quality and availability because of its influence on sediment transport, channel morphology, and streambed substrate characteristics (Trush et al., 2000; Bunn and Arthington, 2002; Brown and Bauer, 2009; Poff et al., 2010). In Clear Creek, flood flows and monthly flows for the months of January through May decreased dramatically from the pre-project period to the first post-project period. Changes in instream flow most likely resulted from reservoir operations since precipitations were not significantly different between these two periods. These dramatic flow reductions and possible associated changes in aquatic habitat may have resulted in the extirpation of spring-run and the substantial reduction of fall-run in Clear Creek in the first post- project period. Spring-run Chinook salmon were extirpated from Clear Creek in the mid-1950s and reintroduced into Clear Creek from 1991 to 1993. Zeug et al. (2010) found that flow alteration below a dam, compared to habitat loss, was a stronger predictor of extirpation of spring-run in the Central Valley. The analysis of post-project flow changes suggests that water operations reduced stream flows during a critical period when adult spring-run were migrating upstream. This substantial change may have contributed to their extirpation because adult spring-run migration coincides with periods of peak flows or the declining limb of high-flow periods in the pre- project period (Zeug et al., 2010).

In this study we revealed when and how changes in streamflow were related to the abundance of salmonids in Clear Creek. As there was little or no salmonid data available for the pre-project period, we are unable to compare the effects of flows on salmonids

Table 4
Best approximating models for spring-run, fall-run, and steelhead. Models are arranged from best to worst based on ΔAIC_c.

Response Variable	Predictor	Month of Predictor	AIC_c	ΔAIC_c	AIC_c Weight	Evidence Ratio
Adult spring-run	Water temperature	June	86.6	0.0	0.846	1.0
		April	90.5	3.9	0.118	7.2
		May	92.9	6.3	0.036	23.6
Juvenile spring-run	Water temperature	September	215.5	0.0	0.815	1.0
		October	219.8	4.3	0.095	8.5
		November	220.0	4.4	0.089	9.1
Adult fall-run	Streamflow	September	430.2	0.0	0.821	1.0
		November	433.7	3.5	0.142	5.8
		October	436.4	6.2	0.036	22.5
Juvenile fall-run	Water temperature	November	354.4	0.0	0.830	1.0
		October	358.9	4.5	0.088	9.4
		September	359.1	4.6	0.082	10.2
Adult steelhead	Water temperature	January	98.2	0.0	0.340	1.0
		December	99.1	1.0	0.209	1.6
		August	99.5	1.3	0.178	1.9
		September	100.6	2.4	0.100	3.4
		November	100.9	2.7	0.087	3.9
		October	100.9	2.7	0.086	3.9
Juvenile steelhead	Water temperature	June	181.4	0.0	0.998	1.0
		July	194.4	13.0	0.002	662.4
		August	196.1	14.7	0.001	1534.7

between the pre- and post-project periods. Although changes in flow magnitude within the post-project period are relatively small compared with flow changes between the pre- and post-project periods, correlations can still be established between flow and fish abundance using the data for the post-project period. With the fish monitoring data available mostly for the second post-project period, we found strong correlations between salmonid (both adult and juvenile) abundance and flow magnitude. Flows in the fall (September through November) are strongly related to the abundance of adult fall-run in Clear Creek, with increasing abundance as flows increase. Adult fall-run start migration into Clear Creek in September. Flows show different relationships to juvenile fall-run; juvenile abundance increases with increasing flows from September to November, but decreases with increasing flows from December to March. Higher flows from September to November appear to benefit adult fall-run for migration and spawning, resulting in higher juvenile abundance, while high flows in winter may negatively affect their very early life stages (i.e., alevin and fry). High flows in late fall and early winter appear to provide benefits for adult steelhead that are migrating into Clear Creek.

It has generally been recognized that streamflow influences adult immigration from estuarine environments to main rivers and from main rivers to spawning tributaries (Arthaud et al., 2010; Marston et al., 2012; Nislow and Armstrong, 2012). The latter phase, referred to as the spawning migration, is best treated as part of the spawning process, as it involves the movement to specific spawning locations, often incorporating a search phase that may include both upstream and downstream movements, which are thought to relate to fish selecting a suitable redd location, finding a potential mate, and locating a safe position to spend time until spawning. Nislow and Armstrong (2012) concluded that adult abundance was correlated to daily flows during the spawning migration period. The timing of spawner arrival was found to be a function of flow regime type and, in particular, antecedent hydrological conditions during the pre-spawning period.

Flows also have a major influence on the growth and survival of juveniles (including fry, parr, and smolt) (Arthaud et al., 2010; Nislow and Armstrong, 2012; Zeug et al., 2014). Stream flows in the lower Stanislaus River were a significant driver of the survival, migration, and size of juvenile fall-run. Greater cumulative flow and flow variability during the out-migration season (from mid-January to late May) promoted higher juvenile survival, higher proportion of pre-smolt migrants, and larger size of smolts (Zeug et al., 2014). In a regulated stream in the Salmon River in Idaho, spring stream flows exhibited strong correlations with egg-to-juvenile and egg-to-adult survival rates for spring-run and were consistently a better predictor of productivity than late summer stream flows. High flows during early rearing were the single best predictor of egg–to-juvenile survival rates (Arthaud et al., 2010). Decreased flow magnitude was generally associated with lower growth rates, resulting in 24–50% decreases in the size of juvenile salmon and trout under low-flow conditions (Nislow and Armstrong, 2012).

Studies have indicated that stream flows impact invertebrate assemblages, which in turn influence the food availability for juvenile salmonids. Yarnell et al. (2013) found differences in both benthic macroinvertebrate diversity and density between regulated and unregulated rivers in the Central Valley. The unregulated study sites exhibited the highest diversity in hydraulic habitat in space and time and the highest diversity in primary productivity. Conversely, the study sites with the most altered flow regimes exhibited the lowest and least consistent hydraulic diversity and the lowest diversity in primary productivity. These differences between unregulated and altered study sites were observed in both study years, regardless of water year type. For the American River watershed, a positively- correlated relationship occurred between the hydraulic diversity and the Ephemeroptera (mayflies)-Plecoptera (stoneflies)-Trichoptera (caddisflies) (EPT) index. The relationship suggests diverse hydraulic niches support diverse benthic macroinvertebrate assemblages (Yarnell et al., 2013).

5.2. *Potential effects of water temperature on salmonids*

Water temperature is an important water quality component because of its enormous significance for all freshwater organisms (McCullough, 1999; U.S. Environmental Protection Agency, 2003; McCullough et al., 2009) and its influence on other aspects of water quality, such as dissolved oxygen, solute and pollutant fluxes, toxicity of pollutants, nutrient concentrations, and organic matter and suspended sediment concentrations (Caissie, 2006; Webb et al., 2008; Olden and Naiman, 2010). Salmonid response to water temperatures may be described as lethal, sublethal, and optimal. High water temperatures can pose lethal or sublethal impacts to salmonids at all life stages, including adult migration, pre-spawn holding, spawning, egg incubation, fry emergence, and juvenile rearing and outmigration (McCullough, 1999; Poole and Berman, 2001; U.S. Environmental Protection Agency, 2003; Jonsson and Jonsson, 2009). With the fish monitoring and water temperature data available mostly for the second post-project period in Clear Creek, we found strong correlations between salmonid abundance (both adult and juvenile) and water temperature, with the general trend being decreasing abundance with increasing water temperature. Water temperatures in June and October were negatively correlated with the abundance of adult and juvenile spring-run in Clear Creek, respectively, as the peak adult spring-run migration into Clear Creek occurs in May and June and spawning peaks in September and October. Water temperatures in the fall (October and November) show negative or curvilinear correlations to adult or juvenile fall-run abundance in Clear Creek. During this period of time, the migration and peak spawning of adult fall-run occur in Clear Creek. When average monthly water temperatures are <14 °C in October and <13.5 °C in November, adult steelhead abundance in Clear Creek increases with increasing water temperature. However, water temperatures in the summer (June and July) were negatively correlated with juvenile steelhead abundance. Juvenile steelhead usually spend two years in fresh water before emigrating (Williams, 2006), and high water temperatures in summer may have contributed to the reduced juvenile steelhead survival in Clear Creek.

Previous studies showed that the embryo survival rate for Chinook salmon showed a sharp increase from 2 °C to 5 °C, remained high from 5 °C to 13 °C, and decreased drastically with water temperatures above 13 °C. The alevin survival rate for Chinook salmon was >0.9 from 2 °C to 14 °C and then decreased sharply with water temperatures above 14 °C (Velsen 1987; Beacham and Murray, 1990). There are temperatures that may not cause mortality to embryos, however, alevins developed under temperatures above 13 °C may be subject to higher mortality at the next developmental stage (McCullough, 1999). Water temperature in Clear Creek has exceeded the water temperature criteria every year since 1997, when measurements of water temperature at Igo began. The water temperature impairment in different months may impact different species or different life stages of the same species. For example, the impairment may affect spring-run and fall-run spawning and egg incubation from September through November, steelhead fry emergence in May, and juvenile rearing in June and July. In September when peak spawning for spring-run occurs, there were 26 and 13 days, on average, exceeding 1 and 2 °C, respectively, above the water temperature criterion for spawning and egg incubation (i.e., 13 °C). The magnitude of the water temperature impairment is sufficient to cause mortality of salmonid embryos (Murray and Beacham, 1987; Murray and McPhail, 1988).

5.3. *Improving flow and water temperature for salmonids*

It is essential to improve both flow and water temperature in order to protect and recover the listed species in Clear Creek and other streams in the Central Valley. Although many restoration activities targeting flow and water temperature have taken place in Clear Creek over the past two decades and Chinook salmon and steelhead populations in Clear Creek have improved, there is still a significant amount of work to do to make the populations sustainable. It is clear that successful implementation of instream flow management below dams must simultaneously consider both discharge and water temperature. Below we discuss how the various flow blocks (i.e., winter and spring base flows, summer and fall water temperature sustaining flows, and specific pulse flows) can be determined and integrated to form an instream flow schedule that creates and maintains key ecosystem functions and biologically-significant habitat features.

5.3.1. *Winter and spring base flow*

Winter and spring base flows in Clear Creek should be relatively high and occur from December through June. These base flows may be prescribed as the percentiles of pre- project flows (Fig. 12). The percentiles may correspond to water year types, for example, 70th, 60th, 50th, 40th and 30th percentiles to wet, above normal, below normal, dry, and critically dry year types, respectively. The relatively high winter and spring base flows provide adequate spawning habitat for adult steelhead and rearing habitat for steelhead and Chinook juveniles, and promote downstream migration of juveniles. Spring base flows are important in providing biological cues for upstream migration of adult spring-run. Spring flows are also critical to riparian vegetation. Shifts in the timing of the start of spring recession flows coupled with higher rates of change can directly affect cottonwood recruitment, whereas decreases in flow magnitude could adversely affect the availability of suitable habitat for cottonwood. Spring recessions declining at a rate of ∼10% per day would ensure a suitable rate of slow decline (Yarnell et al., 2013). For proper cottonwood recruitment, flows must be high enough to initiate bar scour before but not during the reproduction time window. During the reproduction window, flows must be high enough to wet gravel bars and recede slowly enough to allow for germination of seeds (Yarnell et al., 2010).

5.3.2. *Summer and fall water temperature sustaining flow*

Water temperature sustaining flows in summer and fall are needed to reduce stream temperature impairment that may result in lethal or sublethal effects to juvenile and adult salmonids. Elevated water temperature may be reduced by restoring gravel bars and riparian vegetation and releasing cold water from an upstream reservoir. As restoration of riparian vegetation in Clear Creek is difficult, especially in the canyon, cold water reservoir release is an effective means to meet the water temperature criteria. A certain amount of water needs to be released from Whiskeytown Reservoir to meet the water temperature criteria at Igo. The amount of water released can be estimated from the regression model using air temperature (Fig. 9). Note that use of a regression model is limited to the data range of the variables used in building the model. If future observed data are beyond the data range, the regression model may not remain valid. For example, climate change may increase air temperature, and reservoir water temperature may also increase in the future. Although water temperature improvement alone cannot restore native fish populations, it is necessary to restore requisite freshwater habitat for anadromous salmonids. Relatively high freshwater survival is necessary to produce sufficient numbers of spawning adults. Since mortality is high during the freshwater egg-to-smolt periods, reducing mortality during these stages offers significant opportunities for restoration of anadromous fish. Freshwater survival is particularly important during periods of poor ocean productivity (U.S. Environmental Protection Agency, 2001).

Reservoir water should be selectively released from the upper or lower intakes depending on water temperature requirements. For example, in May or June, reservoir water could be released from the upper intake in order to preserve coldwater for later use. In September and October, reservoir water may need to be released from the lower intake in order to maintain water temperature at Igo at 13 °C for spring-run spawning, egg incubation, or fry emergence.

To conserve cold water that could be used in the warmest months, the reservoir has been operated to release more water through the upper intake during the spring and through the lower intake during the summer and fall. We expect that including in the model the water temperature at the dam where the reservoir water is released to Clear Creek would make it more accurate

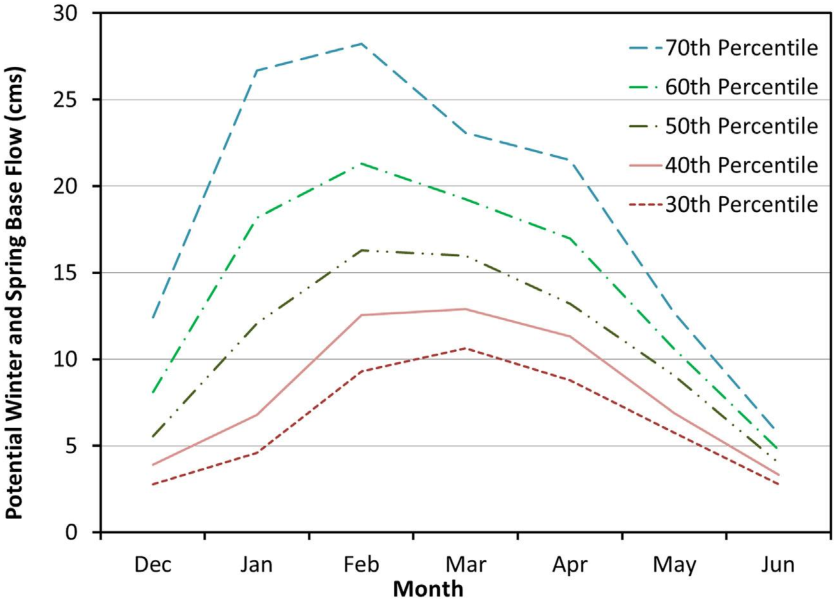

Fig. 12. Range of potential winter and spring base flows in Clear Creek. Each line represents a percentile of the pre-project flows, with the 50th percentile flow being the median flow.

to predict downstream water temperatures. However, the reservoir release water temperature for Whiskeytown Reservoir was not available, precluding the use of a model that has the term of reservoir temperature. This problem may be solved by deploying a water temperature sensor with continuous water temperature measurements at the reservoir discharge point. These water temperature data can be used to rebuild a regression model, thereby improving its prediction accuracy. Reservoir release flows may also be optimized for migration, growth, and survival using individual-based or quantile-based models as demonstrated for Chinook salmon in the Tuolumne River, California by Jager (Jager et al., 1997; Jager and Rose, 2003; Jager, 2014). Another beneficial investment is to develop a physical process based reservoir temperature model coupled with a riverine model, which can be used to predict the proportion of flow releases from the upper and lower intakes in order to conserve coldwater while meeting water temperature criteria at Igo for various life stages of fish species present in Clear Creek.

5.3.3. *Spring pulse flow*

Other functional flows include spring pulse flows that remove fine sediments, organic matter, and detritus from the interstitial voids in channel coarse substrates and depositional areas, thereby improving spawning habitat. Spring pulse flows also attract adult spring-run and improve access to upstream areas or to downstream areas for juvenile Chinook salmon and steelhead. Spring pulse flows are greater in magnitude than spring base flows. They are usually shorter in duration (a few days) and contained within the channel at or above the half-bankfull discharge level for most streams. The IHA analysis shows that during the pre-project period the median magnitude of spring pulse flows in Clear Creek was 17 cms with a frequency of twice a year from March through April, and the median duration of spring pulse flows was 5 days with a rise rate of 6 cms/day and a fall rate of 4 cms/day.

There is concern about potential negative impacts of pulse flows on existing steelhead redds in the streambed. Although high flow conditions are perceived to pose a potential risk of embryo mortality through scour and/or mechanical shock, direct observation of such effects is relatively rare. In process-based studies where scour has been considered in the context of salmon spawning locations, there is a general indication that redd washout may be less common than is often perceived. Montgomery et al. (1996) established that scour depths associated with mean annual flood events in Pacific Northwest streams did not generally exceed the burial depths of chum salmon, *Oncorhynchus keta* (Walbaum). They suggested that salmonids have evolved to bury their eggs at locations and depths where, in a typical year, scour would not result in the loss of embryos. Moir et al. (2009) showed that spawning generally occurred at relatively stable locations with low excess sheer stress; similarly, May et al. (2009) found that spawning locations were generally less susceptible to scour as they were found in relatively shallow water areas with coarse substrate.

5.3.4. *Winter floodplain inundation flow*

Floodplain inundation flows are flood flows with the return interval of 1.5–2 years. The IHA results indicated that the magnitude of pre-project floodplain inundation flows in Clear Creek was 174 cms with a rise rate of 31 cms/day and fall rate of 7 cms/day. If these types of flood flows are coincident with the first flush event that follows an extended dry period, they would provide additional benefits such as mobilizing nutrients and turbidity and diluting contaminants.

Floodplain inundation flows usually cover stream banks. They allow fluvial processes to reshape and maintain a new dynamic river channel and provide favorable physical habitat conditions for juvenile and adult salmonids in Clear Creek. For example, these flood flows create and maintain alternating point bars and associated riffles and pools, which are the primary geomorphic units of alluvial rivers and represent a key habitat template for all freshwater life stages of anadromous salmonids as well as other stream biota (Trush et al., 2000). Hyporheic flow, which is colder than surface water in warm seasons, occurs between alternating pool/riffle sequences in the stream channel. Water enters the streambed (*i.e.*, the alluvial aquifer) at the downstream end of pools, flows through the streambed sediments, and reemerges at a downstream riffle. Channels with complex streambed topography have higher rates of streambed hyporheic flow (Poole and Berman, 2001). Using the quantile model approach, Jager (2014) showed that winter floodplain inundation flows will benefit salmon production by speeding growth and expediting out-migration from rivers that become inhospitable in summer.

Floodplain inundation flows will help to create and maintain several different types of habitats for salmonids, for example, pools for adult holding and juvenile rearing in warm seasons, adequate substrate and hydraulic conditions for spawning, and floodplain habitat for juvenile rearing. Chinook salmon rearing on California floodplains have been found to grow significantly faster than fish in the main channel (Sommer et al., 2001; Jeffres et al., 2008). The highest quality rearing habitat for salmonid fry is often found along the shallow, slow velocity margins of alternate bars, where coarse sediments (gravels and cobbles) provide interstitial hiding places, productive invertebrate (food) habitat, and access to high flow refugia on top of lateral bars.

5.3.5. *Integration of flows*

Fig. 13 shows an example instream flow that integrates various flow blocks for Clear Creek: the median winter and spring base flows, spring pulse flows, and summer and fall water temperature sustaining flows. For comparison, mean flows for both pre-project and the second post-project periods are also presented. From January through June, base flows dominate the instream flow, while from July through October water temperature sustaining flows dominate the instream flow in Clear Creek. Instream flows in November and December are maintained at the same level as that in October to avoid potential dewatering of spring-run and fall-run redds and to provide rearing habitat for juveniles. Maintaining flows in November and December similar to those in October provides multiple benefits to juveniles. During this period of time, the eggs of spring-run have hatched and fry have emerged from the spawning bed. Flow alteration during the fry life stage can have important impacts on survival and growth. Reducing flow, even if gradual, could disconnect rivers from their side channels and reduce the availability and quality of shallow water habitat required by fry. An important consideration for the fry stage is that suitable habitats for feeding may be in limited supply because only a narrow range of microhabitats appear to yield favorable foraging conditions. Suitable habitats are also potentially limited by the presence of other larger older fish, which may exclude fry from the habitats that these larger fish prefer. Competition for this limited number of suitable habitats is intense; in some situations, a large majority of fry fail to locate suitable habitats and succumb to starvation (Nislow and Armstrong, 2012). Fry are also highly vulnerable to predation during emergence. As a result, mortality is generally very high at this life stage.

The annual hydrograph of the example instream flow is similar to the flow pattern for the second post-project period of 1995–2013 (Fig. 13). However, the example winter and spring base flow, which represents a more natural flow regime, is higher than the second post-project flow. These higher base flows will provide benefits to Chinook salmon and steelhead adult immigration and spawning and juvenile rearing and outmigration (Fig. 14). Flows in September and October are also higher than the second post-project flows in order to sustain appropriate water temperatures for spawning, egg incubation, and fry emergence of spring-run. The enhanced flows in September and October will also provide benefits to adult immigration of steelhead and fall-run and adequate water temperatures for fall-run spawning (Fig. 14).

The flows in the summer and fall (July through October), as shown in Fig. 13, are higher than the pre-project hydrograph in order to sustain water temperatures not exceeding temperature criteria for salmonids. However, the lower pre- project flows in the summer and fall do not necessarily indicate higher water temperatures that salmonids had experienced. This may be explained with several reasons. Riparian vegetation coverage could be better prior to development, resulting in cooler water temperature in general. Undisturbed forest and substrate might contain higher moisture and more groundwater that are sources of coldwater discharge to the stream. Finally, pre-project hydrography with more frequent and high-magnitude flows in the winter and spring creates and maintains large and deep pools in the stream, providing coldwater refugia for salmonids during the hot and dry summer and fall seasons.

The magnitude of the flow regime as described in our paper is less than 30 cms except for the floodplain inundation flow. The combined discharge capacity from the two intakes of Whiskeytown Reservoir is about 52 cms. The floodplain inundation flow of 174 cms can be achieved through the use of a major winter storm event and the spillway. The spillway consists of a morning-glory inlet and ogee crest structure, a vertical transition curve, a tunnel, and a flip-bucket energy dissipater. The discharge capacity of the spillway is 811 cms at a water surface elevation of 372 m. Historical records show that a flow of about 200 cms in 1998 had no recorded damages (U.S. Bureau of Reclamation, 2009).

The natural flow regime-based approach has been used to effectively manipulate and manage fish assemblages in lower Putah Creek, a regulated river in the Central Valley (Kiernan et al., 2012). During the eight years of monitoring before the natural flow regime was implemented, native fishes were constrained to habitat immediately (<1 km) below a diversion dam, and alien species were numerically dominant at all downstream sample sites across more than 20 km of lower Putah Creek. During nine years following implementation of the new flow regime, native fishes regained dominance. The expansion of native fishes was facilitated by creation of favorable spawning and rearing conditions (*e.g.*, elevated springtime flows), cooler water temperatures, maintenance of lotic (flowing) conditions over the length of the creek, and displacement of alien species by naturally occurring high-discharge events. Importantly, restoration of native fishes was achieved by manipulating stream flows at biologically important times of the year and only required a small increase in the total volume of water delivered downstream (*i.e.*, water that was not diverted for other uses) during most water years. As described in this study, the example flow regime in Clear Creek includes several key flow components important for migration, spawning, egg incubation, and rearing. The example flow as shown in Fig. 13 would have a 35% increase in annual flow comparing to the average flow of the second post-project period (1995–2013).

5.4. *Instream flow implementation and adaptive management*

The biology of salmonids includes multiple life stages—adult immigration (and holding), spawning, egg incubation, fry and parr rearing, and smolt out- migration—that are closely linked to flow regimes. Managing flows based on the needs of individual species or specific life stages of species may generate conflicting effects during a season (*e.g.,* low flows may favor fry survival, but at the cost of smolt migration success). Managing flows to follow a more natural regime not only reflects the evolutionary adaptation of these species to the natural hydrology but also helps to minimize potential conflicting effects. Realizing that channels and their geomorphology have also been changed substantially in many regulated rivers, implementing new flow schedules requires an adaptive management process where the effects of provisional flows are monitored and tested, thereby providing critical data to inform both science and water management.

The effectiveness of implementing instream flows to achieve targeted benefits could be determined through consistent monitoring of the response. Implementation and monitoring programs should occur in parallel. Before an action is implemented, baseline conditions should be clearly documented (Kiernan et al., 2012). A monitoring plan could include measurements of streamflow, water

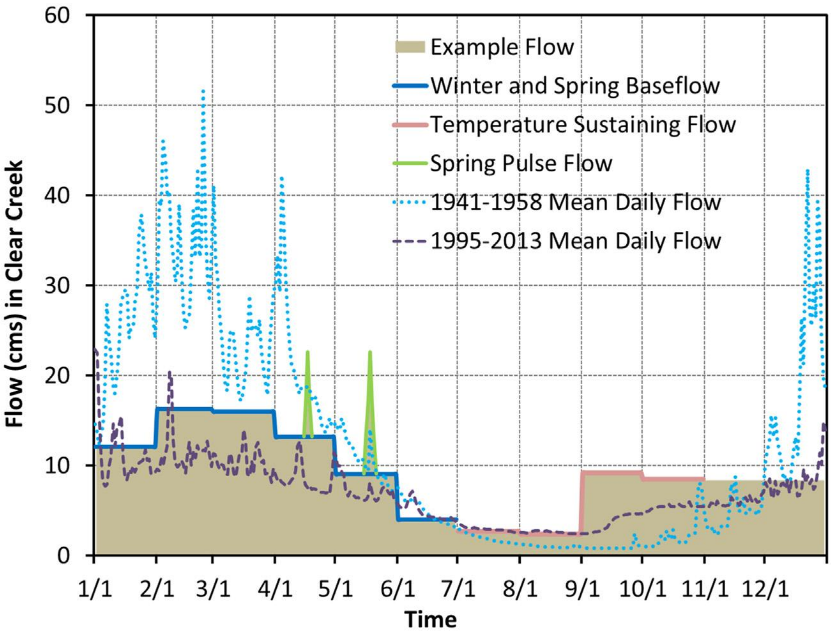

Fig. 13. An example instream flow hydrograph together with the median winter and spring base flow, spring pulse flows, and summer and fall water temperature sustaining flow in Clear Creek. Also shown are the mean daily flows for the pre- and second post-project periods.

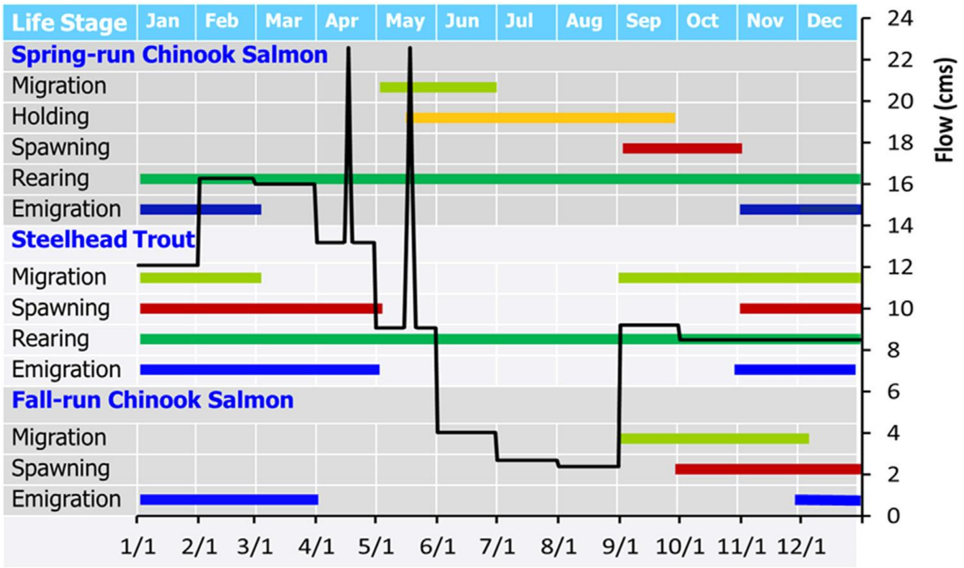

Fig. 14. A diagram showing the example instream flow (black line) related to the life stages of the three anadromous fish species in Clear Creek. Horizontal bars indicate time periods in month for life stages including migration and spawning for adults, and rearing and emigration for juveniles. For example, spring-run adults migrate into Clear Creek in May and June. The holding life stage is for spring-run adults only.

temperature, weather condition, fish biology, macroinvertebrate community, and stream morphology. Analysis, synthesis, and evaluation of the actions and monitoring are critical to improve current understanding. Analysis and synthesis should be informative of how conditions have changed, in both expected and unexpected ways, as a result of the implementation of the actions. The evaluation should examine whether or not one or more of the performance measures have been met as a result of the implemented actions and why. If a performance measure is not met, an explanation of the potential reasons why this measurement has not been met should be clearly identified and communicated. The adaptive management process aims at addressing the following questions: (1) Have the prescribed flows been met? (2) Have the temperature requirements been met? (3) Have the flows improved geomorphic processes? (4) Has the fish habitat been improved? And (5) have the improved flow, water temperature, and physical habitat conditions supported positive biological effects on salmonid adults and juveniles? While reading down the list of questions above, each becomes more difficult to answer by monitoring alone. For example, daily flow data or hourly water temperature data can be used to evaluate to what degree the alternative reservoir releases improve flow and water temperature; however, proper evaluation of changes in fish populations may take decades (Kiernan et al., 2012). In addition, both the uncertainty of parameter measurement and the impact of confounding factors increase over time.

In conclusion, both flow and water temperature are critical to the survival and growth of salmonids in the Central Valley where instream flow has been substantially altered and water temperature impaired. Water temperature must be taken into account in developing flow regimes in order to conserve and recover endangered, threatened, or concerned salmonid species in the Central Valley. Although we used Clear Creek to demonstrate how this methodology works, the framework described in this study can be applied to other regulated streams in the Central Valley or other Pacific regions. Instream flow and water temperature are among the major factors that have caused the dramatic decline of salmonid populations in the Sacramento and San Joaquin Rivers. Instream flows in a number of tributaries to these two rivers are regulated by upstream reservoirs, and the framework can be readily applied to those regulated tributaries for developing instream flows. These ecosystem-based flows can serve as the foundation for recommending a flow regime to restore a degraded aquatic ecosystem while considering other beneficial uses and constraints.

The flow regime developed in this study did not consider the potential impacts of future climate change on precipitation, stream flow and temperature, and salmonid species in the Central Valley (Cloern et al., 2011; National Research Council, 2012; Moyle et al., 2013). Cloern et al. (2011) projected that, by 2100, less water will be available due to decreasing precipitation, and stream temperature will increase to the extent that much of the currently available spawning and rearing habitats will no longer be suitable for salmonids in the Central Valley. Long-term strategies for species recovery, which should consider the effects of climate change, will likely require reintroduction of these salmonid species to historical coldwater habitats above the dams in the Central Valley (National Marine Fisheries Service, 2014) and other similar regions (Anderson et al., 2014; Galbreath et al., 2014). Although potential evolutionary changes in migration timing might eventually allow some salmonid species to avoid warm stream temperatures (Reed et al., 2011), a short-term solution is needed to support species conservation. The method described in this work identifies adequate stream flow and temperatures that are essential to a short-term conservation solution.

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