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RESEARCH ARTICLE

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Managing hydropower dam releases for water users and imperiled fishes with contrasting thermal habitat requirements

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Abstract

1. The construction of dams on large rivers has negative impacts on native species. Environmental flows have been proposed as a tool to mitigate these impacts, but in order for these strategies to be effective they must account for disparate temperature and flow needs of different species.
2. We applied a multi-objective approach to identify trade-offs in dam release discharge and temperature for imperiled fishes with contrasting habitat requirements, while simultaneously meeting the needs of human water users.
3. Using the Sacramento River (California, USA) as a case study, our model suggests that current management aimed at providing high discharge for downstream water users and cold water for endangered winter-run Chinook salmon (*Oncorhynchus tshawytscha*) has detrimental impacts on threatened green sturgeon (*Acipenser medirostris*), which require warm water for juvenile growth.
4. We developed an optimal dam release scenario that can be used to meet the needs of salmon, sturgeon and human water users. Our results show that dam releases can be managed to successfully achieve these multiple objectives in all but the most severe drought years.
5. *Synthesis and applications*. This study shows that managing dam releases to meet the needs of a single species can have detrimental effects on other native species with different flow and temperature requirements. We applied a multi-objective approach to balance environmental requirements of multiple species with the needs of human water users. Our findings can be used to guide management of Shasta Dam and our approach can be applied to achieve multi-object management goals in other impounded rivers.

KEYWORDS
designer flows, Endangered Species Act, green sturgeon, hydropower proliferation, multi-object optimization, multi-species management, Paris Agreement, winter-run Chinook

1 | INTRODUCTION

In the last decade, there has been a massive increase in the number of proposed hydropower projects around the world (Zarfl, Lumsdon, Berlekamp, Tydecks, & Tockner, 2015). This proliferation has gained momentum in response to the 2015 Paris Agreement, which identified hydropower as the renewable energy replacement for fossil fuels (Hermoso, 2017; UNFCCC, 2015). It has been well documented that dams alter downstream conditions such as flow timing, flow amplitude and river temperature (Olden & Naiman, 2010; Richter & Thomas, 2007). The disturbance of the river environment downstream from dams reduces biodiversity and changes community structure (Poff, Olden, Merritt, & Pepin, 2007; Stanford & Ward, 2001; Wootton, Parker, & Power, 1996). However, dams are also used to deliver water, prevent floods and generate electricity at peak times. Dam releases must therefore be managed to sustain aquatic habitat while delivering human services. The United States Endangered Species Act (ESA) mandates flow targets for individual species, which are met using dam releases to modify discharge and/or temperature (Olden & Naiman, 2010; Poff et al., 1997). Specific flow designs may provide opportunities to simultaneously meet downstream human and wildlife needs (Chen & Olden, 2017).

Dams prevent cold-water reliant fish species from reaching lower order streams, whereas altering temperatures in mainstem rivers inhabited by warm-water species. Cold-water species must instead carry out their life history in the warmer mainstem. Targeted flows can release cold water (Olden & Naiman, 2010), but the release of cold water can negatively impact warm-water species. This alters mainstem habitat, pushing warm-water organisms further down in the river system where temperatures warm to acceptable levels**.** Natural flow regimes can be restored for communities of native fishes using targeted releases (ESSA, 2017; Kiernan, Moyle, & Crain, 2012), and many studies focus primarily on identifying and mimicking ecologically relevant components of the natural hydrograph (Poff et al., 2010; Yarnell et al., 2015). However, flows have not yet been designed for co-occurring species with conflicting temperature tolerances. Here, we use a case study of a warm- and cold-water Endangered Species Act (ESA) listed species in California's Sacramento River to ask whether flows can be designed to simultaneously meet the needs of cold- and warm-water fish species and downstream human use.

The Sacramento River provides 35% of California's water supply but also contains unique genetic and life-history diversity for several anadromous fish species listed under the US Endangered Species Act (ESA) (Grantham et al., 2017). The spawning grounds of two ESA-listed species, endangered Sacramento River winter-run Chinook salmon (hereafter referred to as winter-run; *Oncorhynchus tshawytscha*) and threatened green sturgeon (*Acipenser medirostris*), did not overlap in the Sacramento River. Winter-run spawned in high-elevation cold habitat, whereas green sturgeon spawned in the warm mainstem (Figure S1; Fisher, 1994; Mora, Lindley, Erickson, & Klimley, 2009). The optimal rearing temperature for larval green sturgeon is 19°C, whereas survival of incubating winter-run eggs begins to decrease above 12°C (Martin et al., 2017; Poletto et al., 2018). These differences in temperature tolerance between the two species lead us to classify green sturgeon as a 'warm-water species' and winter-run as a 'cold-water species' for the purposes of this manuscript, although these are relative classifications that are specific to this system. After the construction of Shasta Dam in 1945 blocked access to historical spawning habitat, both species began spawning in the mainstem below the dam (Figure 1). Winter-run chinook dig gravel redds in the cold outflow from the dam, whereas green sturgeon broadcast spawn further downstream in strong eddies with varying benthic habitat (Wyman et al., 2017). These habitat displacements are a conservation concern because both distinct

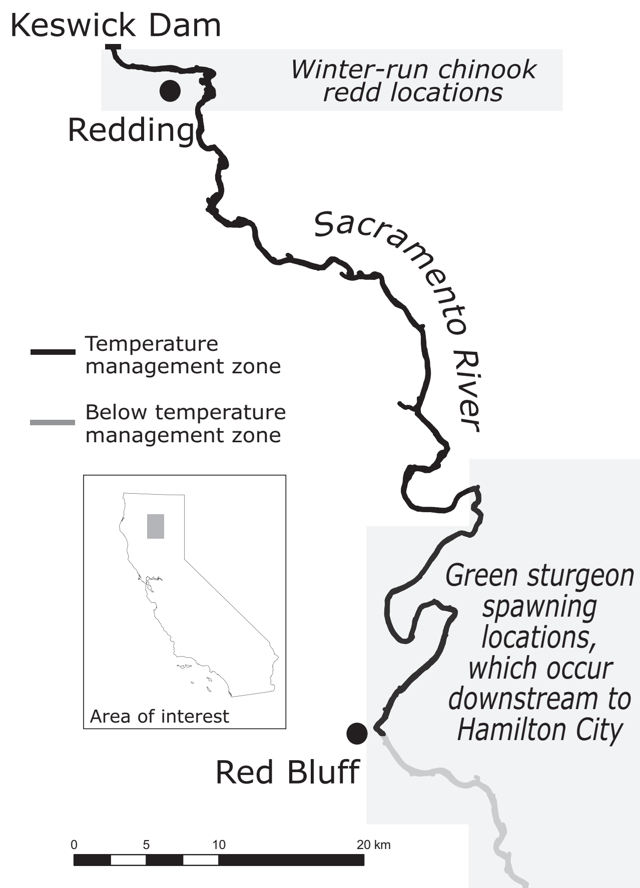

FIGURE 1 Map of the Sacramento River below Keswick Dam (the afterbay to Shasta Dam) to Red Bluff, with river regions of Sacramento River winter-run Chinook redds, green sturgeon spawning and temperature management

population segments are endemic to Central Valley watersheds, and these compounding factors have led to the ESA-listing of both species. Current management provides cold water for winter-run egg survival using a temperature control device (TCD), which allows selective withdrawal of cold hypolimnetic and warm epilimnetic flows from Shasta Reservoir. Selective withdrawal is the most effective method of control release temperature, although there are several other techniques (Olden & Naiman, 2010). The river below Shasta Dam is now much colder than it was historically, and this cold water extends into current green sturgeon spawning grounds (Figure S1). Cold-water pollution below dams dramatically impacts mainstem ecosystems that are adapted for warmer temperatures (Astles, Winstanley, Harris, & Gehrke, 2003). Larval green sturgeon growth, food consumption, food conversion efficiency and diet indices are positively influenced by warmer temperatures (Mayfield & Cech, 2004; Poletto et al., 2018; Zarri & Palkovacs, 2018), suggesting that cold releases for winter-run may negatively impact green sturgeon.

During the temperature management season for winter-run (May–November), Shasta Dam releases maintain cold temperatures for incubating eggs and deliver adequate discharge for downstream water users. The current management strategy aims to maintain river temperature at or below the experimentally derived threshold

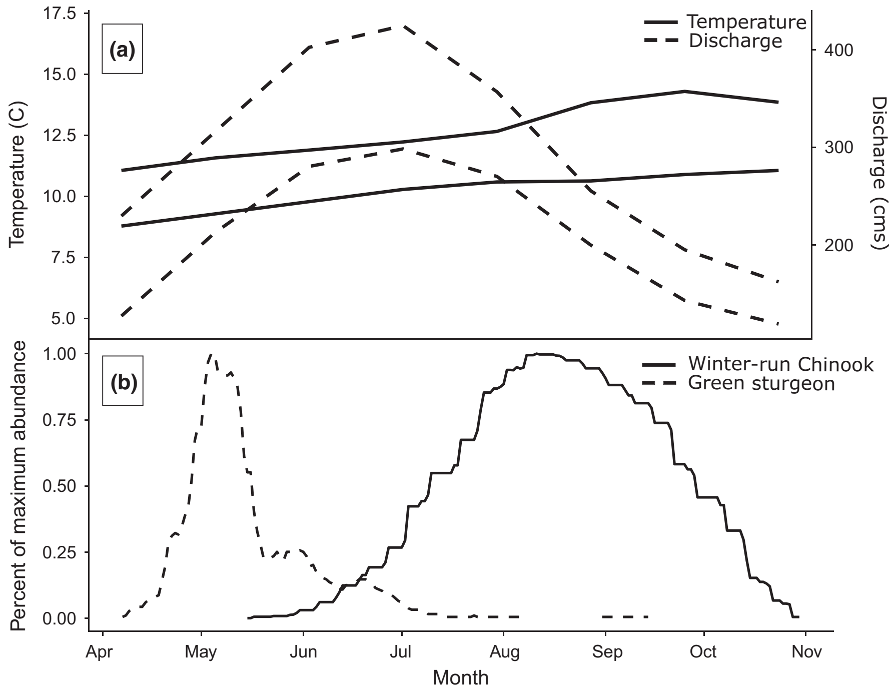

FIGURE 2 (a) Historic temperature (10th and 90th quartiles) and discharge (25th and 75th quartiles) releases from Keswick Dam by month from 1990 to 2016, and (b) temporal distribution of Sacramento River winter-run Chinook eggs and green sturgeon larvae presence above Red Bluff Diversion Dam

of 13.3°C for winter-run egg survival (USFWS, 1999). Recent work suggests that dam releases should be even colder to reduce winter-run egg mortality (Martin et al., 2017). Green sturgeon spawning temporally overlaps with the temperature management season and winter-run spawning, and previous models suggest that there may be a temperature management trade-off between the two species (Hamda et al., 2019). Downstream water users and winter-run require certain minimum discharge levels, but the impact of discharge on wild larval green sturgeon remain unknown. We examined the water management options for the Sacramento River to determine if there is an optimal balance for winter-run, green sturgeon and downstream water users.

We used 5 years of green sturgeon and winter-run data from 2012 to 2016 to ask three questions: (a) Do the water temperature targets for winter-run egg development create suboptimal conditions for larval green sturgeon? (b) Do dam release strategies exist that optimize management of winter-run, green sturgeon and downstream water users and (c) how often are optimal release strategies feasible given inter-annual variability in hydrology and meteorology? We adapted models of winter-run egg survival (Martin et al., 2017) and developed a statistical predictive model for green sturgeon body condition to understand their responses to dam release temperature and discharge. There are other ESA-listed species in this system such as California Steelhead (*Oncorhynchus mykiss*) which are likely impacted by altered flow regimes, but there is not enough empirical data on these species to integrate them into our model. To understand the trade-offs in dam release scenarios for both species and water users, we combined the two species models in a multi-object optimization model (Horne et al., 2017; Polasky, Nelson, Lonsdorf, Fackler, & Starfield, 2005). We optimized dam releases for winter-run and green sturgeon during the months they are both present (Figure 2b) after constraining management scenarios to those which meet the discharge requirements of water users, based on the past 20 years of dam discharge release (Figure 2a). Finally, we used a mechanistic water temperature model of Shasta Reservoir to estimate the proportion of years the scenario was feasible.

2 | MATERIALS AND METHODS

We first compared health metrics for both species across 2012–2016. Winter-run egg-to-fry survival was calculated as the estimated number of surviving fry in Red Bluff Diversion Dam (RBDD) screw traps divided by estimated egg production (National Marine Fisheries Service, 2013–2017; Figure 1). We limited our analysis to exogenously feeding larval green sturgeon at approximately 2 weeks post hatch (Supporting Information). Samples were collected via rotary screw traps which we assumed to sample fish randomly and not select for specimens of particular body condition. The green sturgeon health metric was body condition, because there are no data available on green sturgeon egg production. Larval body condition is a commonly used indicator of fat reserves and health, and has been associated with health in sturgeon (Froese, 2006; Kappenman, Fraser, Toner, Dean, & Webb, 2009). To estimate the temperature and discharge dam releases across the season, we modelled average temperature and discharge for each month of the year that early life stages of either species were present in the study area using data from the River Assessment for Forecasting Temperature model (RAFT; Daniels, Sridharan, John, & Danner, 2018; Pike et al., 2013).

Next, we developed statistical submodels elucidating the impact of river temperature and discharge on winter-run and green sturgeon. To place both submodels in the context of dam release scenarios, we estimated differences in discharge and temperature between Keswick Dam (the afterbay to Shasta Dam) and each species' environment. During the summer and fall, the river warms as it moves downstream from Keswick Dam, increasing 0.46°C (σ = 0.06°C) to the downstream boundary of winter-run redd locations and 2.20°C (σ = 0.52°C) to the green sturgeon spawning locations. We assumed constant temperature and discharge throughout winter-run embryonic development as data on individual redds were not available. Standard deviation in temperature and discharge during development (hatch to capture) of larval green sturgeon was not a significant predictor in our model and therefore we included only mean development temperature and discharge. The winter-run model identified the probability of egg temperature-based mortality (Martin et al., 2017). This is an additive model across the egg incubation period, given by:

$$M_T = 1 - \prod_{i=1}^{n} exp\left(-\left(b_T \max\left(T_i - T_{crit}, 0\right)\right)\right)$$

where M_T is predicted temperature dependent mortality between egg fertilization and completion of the alevin stage T_{crit} is the temperature threshold above which mortality begins to increase and T_i is the daily temperature for day *i* until alevins emerge at day *d*. b_T is the slope of mortality rate above T_{crit} and these parameters are estimated in Martin et al. (2017) as 0.024 and 12°C, respectively. *n* is number of days to maturation, modelled using relative developmental state which is 0 at fertilization and increases at rate 0.001044(°C^{-1}d^{-1})*T_i + 0.00056(d^{-1}) until completion of the alevin stage at 1 (Zeug, Bergman, Cavallo, & Jones, 2012). Due to lack of supporting data, we assumed no impact of discharge on egg survival. Low discharge can cause redd desiccation, but this is rare with high summertime water demands downstream. We developed the green sturgeon submodel (See Supporting Information) to predict body condition over the ~14 days until they pass RBDD:

$$K = b_T \cdot T_i + b_D \cdot D_i + x$$

where *K* is predicted body condition, b_T is the coefficient for the effect of mean temperature T_i until individuals pass RBDD, b_D is the coefficient for the effect of discharge D_i until individuals pass RBDD and *x* is the intercept (estimated in Supporting Information).

We combined both statistical submodels in a multi-object optimization model to calculate optimal dam release temperature and discharge when early life stages of both species are present. No weighting was applied to either objective, and data came from 2012 to 2016. Each management strategy was plotted with *x* as the response of objective 1 and *y* as the response of objective 2. A Pareto frontier indicated optimal solutions (Deb, 2014). A Pareto frontier containing a corner on a high value for both objectives highlights the optimal strategy, whereas a straight or curved line indicates trade-offs. The optimal dam release scenario was calculated by scaling each response from zero to one, then multiplying the scaled response for each species against one another for each scenario. The highest score indicated the optimal scenario. Dam release discharge is limited by requirements of downstream water users, whereas temperature is limited by the available volume of cold water in the reservoir hypolimnion and warm water in the epilimnion. Therefore, we constrained monthly discharge to the 25th–75th percentile and temperature to the 10th–90th percentile of 1996–2016 (Figure 2a).

To evaluate the probability of achieving the optimal dam release scenario through the season, we used a mechanistic reservoir water temperature model of Shasta Reservoir that has been calibrated to the system (Daniels et. al., 2018). We ran each year independently with inputs of observed hydrological and meteorological conditions from 2000 to 2015. Rather than using actual dam release discharge and temperature, discharge was set to the optimized monthly value and a selective withdrawal algorithm was used to select the TCD gate to open on a given day such that reservoir discharge temperature not exceed the optimal temperature target (Figure S4).

3 | RESULTS

Body condition of larval green sturgeon was positively correlated with temperature (linear regression: p < .001, R^2 = 0.07, *F*-statistic = 19.21, 95% confidence interval of slope = 0.13–0.24), and negatively correlated with discharge (linear regression: p < .001, R^2 = 0.13, *F*-statistic = 39.63, 95% confidence interval of slope = −0.002 to −0.0009) (See Supporting Information). The cold, high discharge years of 2012–2013 had high winter-run egg survival and poor green sturgeon condition (Figure 3). The warm, low flow drought years of 2014–2015 had low winter-run egg survival and higher green sturgeon condition. In 2016 both winter-run and green sturgeon biological metrics were higher than average.Figure 3 Average environment and biological response across the 5 years of this study. (a) The mean temperature (solid line) and discharge (dashed line) at Keswick Dam from April to November across the 5 years of this study. (b) Green sturgeon body condition (dotted and dashed line) and Sacramento River winter-run Chinook egg-to-fry survival (dotted line)

Combining the two statistical submodels in a multi-object optimization model indicated that there is an optimal management strategy. The submodels predict how a range of dam releases observed through the season (10°C–13°C, 150–450 cms) alter green sturgeon body condition and winter-run egg-to-fry survival (Figure 4a). The multi-object optimization model combined submodels for each species across their development periods (x-axis and y-axis, respectively, Figure 4b). The Pareto frontier identified an optimal release corner for both species that was also constrained by thresholds of water user discharge, located at the dam release of 150cms discharge with 11.5°C Keswick temperature (Figure 4b).

The optimal management scenarios with the reservoir temperature model indicated which objectives were achievable based on data from 2000 to 2015 (See Figure S4). The water user objective was minimum dam release discharge (25th quartile, Figure 2a) and species objectives are listed in Table 1. The minimum discharge objective for water users was achievable in all years except for the critically dry 2014. The temperature objective of below 11.5°C at Keswick from

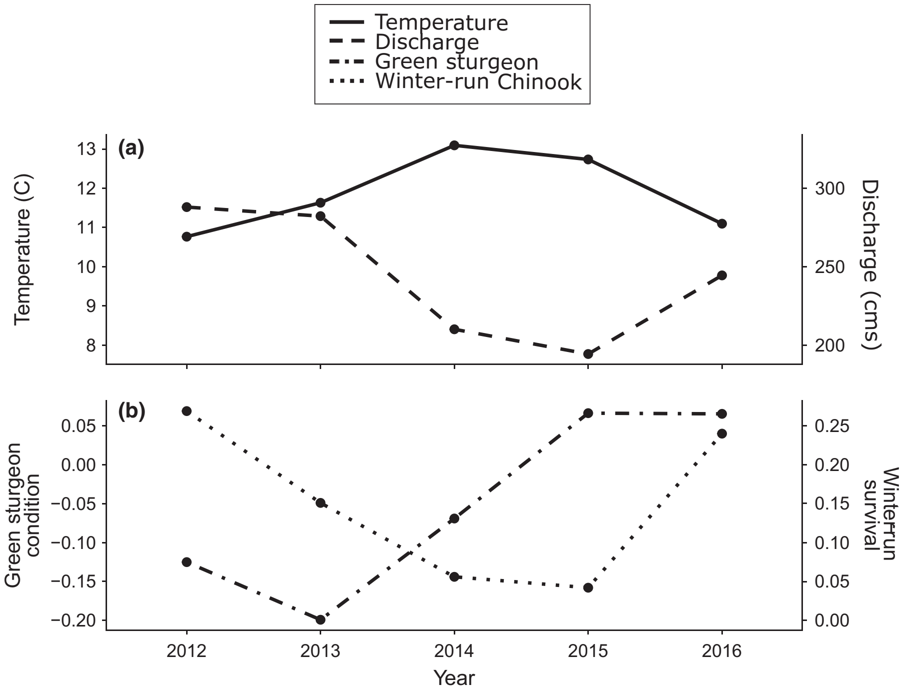

FIGURE 2 (a) Historic temperature (10th and 90th quartiles) and discharge (25th and 75th quartiles) releases from Keswick Dam by month from 1990 to 2016, and (b) temporal distribution of Sacramento River winter-run Chinook eggs and green sturgeon larvae presence above Red Bluff Diversion Dam

June to December for winter-run was achievable in 75% of years. The temperature objective of warm temperatures from March to May for larval green sturgeon was achievable in 56% of years, and warm temperatures were usually only reached at the end of the larval green sturgeon season. However, the low discharge objective from March to May for larval green sturgeon was achievable in 94% of years. All three objectives are met in 69% of years if the larval green sturgeon discharge threshold is used, whereas the three objectives are met in only 50% of years if the larval green sturgeon temperature threshold is used. These probabilities can be projected into the future, assuming that the past 20 years are reflective of the future.

4 | DISCUSSION

California's Sacramento River supports the largest agricultural economy in the United States and is home to unique and imperiled cold- and warm-water fish species (Grantham et al., 2017). Here we show that flow regimes can be designed to balance the needs of warm- and cold-water fishes while simultaneously meeting downstream water user requirements. The current management approach for the Sacramento River uses water releases from Shasta Dam to maintain cold temperatures for developing ESA-endangered winter-run eggs while delivering adequate discharge for downstream water users. These two objectives are of primary importance for Shasta Dam releases but likely harm ESA-threatened green sturgeon, which depend on warm low flow conditions to support larval growth. High discharge has a strong impact on developing green sturgeon larvae swimming ability and is associated with decreased prey richness and diet count (Verhille et al., 2014; Zarri & Palkovacs, 2018). By introducing larval green sturgeon condition to a winter-run egg survival model in multi-object optimization, we identify a Pareto frontier with a corner that is optimal for both species. Our study corroborates others which found that indices of health in larval green sturgeon are enhanced at higher temperatures (Hamda et al., 2019; Mayfield & Cech, 2004; Poletto et al., 2018; Zarri & Palkovacs, 2018), but body condition appears to be more sensitive to changes in discharge at the range of environmental variables experienced in our study region (Figure 4a). Furthermore, the positive correlation of green sturgeon body condition with temperature may be moderated by food availability, as fish exposed to warm temperatures with low food availability show very low body condition (Poletto et al., 2018). The optimal dam release, which is only necessary during the time that both species are present in the managed portion of the river, is 11.5°C and 150cms (Figure 4b).

Optimal temperature management for both species is possible given the natural warming of water as it flows downstream from winter-run redd sites to green sturgeon spawning sites. The low discharge requirements of green sturgeon conflict with high discharge requirements of water users, but larval green sturgeon are mostly present in May, whereas peak agricultural water demand is June-July. Given the temporal variation in species presence and water user requirements, we proposed environmental flows to balance winter-run egg survival and larval green sturgeon body condition while meeting requirements of downstream water users (Table 1). Releasing warm water earlier in the season for larval green sturgeon may preserve cold water for winter-run later in the season (Hanna, 1999; Nickel, Brett, & Jassby, 2004). In most years this strategy would improve conditions for larval green sturgeon without harming winter-run or water users. However, conflict is unavoidable under severe drought conditions, as occurred in 2015.

The reservoir water temperature model indicated that discharge and temperature optimums were achievable in 69% of

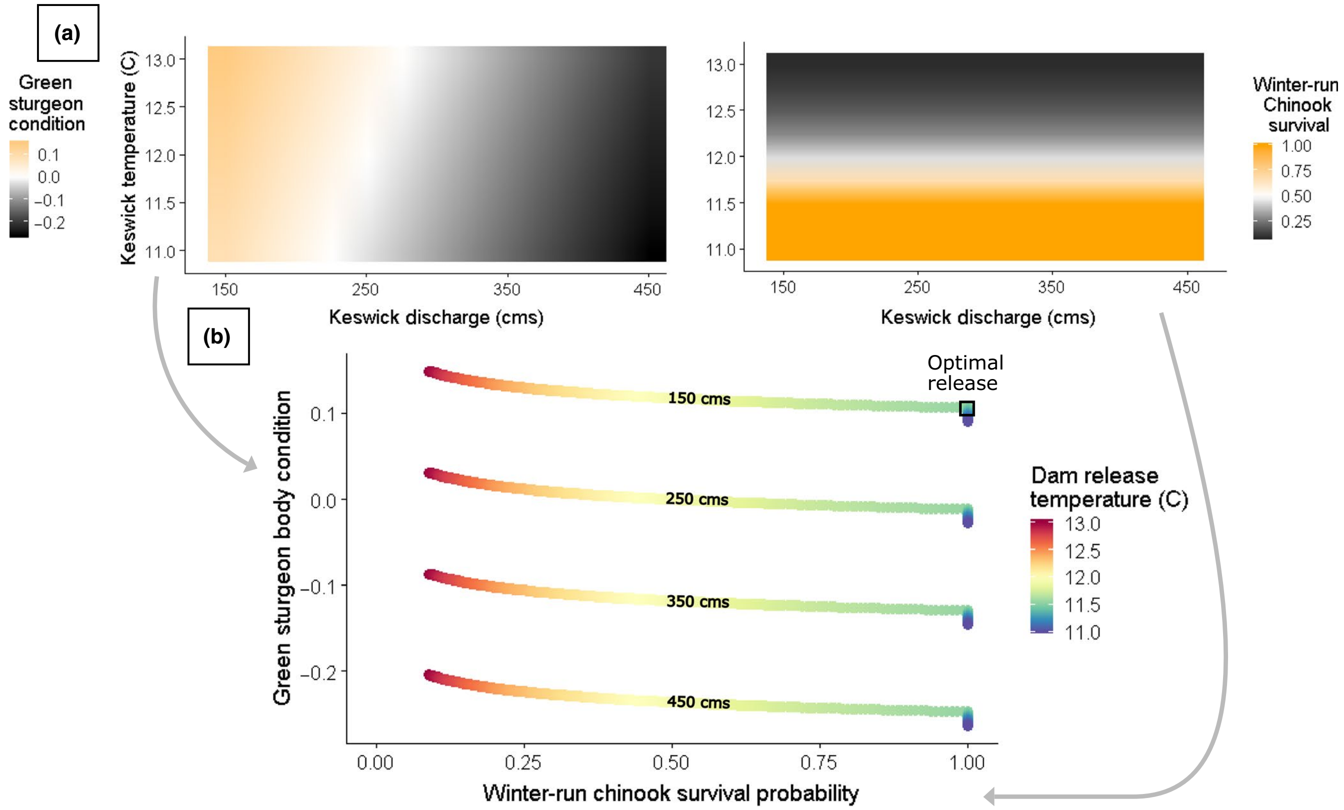

FIGURE 4 (a) Impact of Keswick Dam temperature and discharge on relative body condition of larval green sturgeon and egg-to-fry survival of Sacramento River winter-run Chinook. (b) Multi-object optimization model generated by modelled response of Sacramento River winter-run Chinook and green sturgeon to Keswick dam release temperature and discharge. The optimal solution can be visually identified as there are just two objectives. The coloured lines indicate the minimum discharge Pareto frontiers. For example "150 cms" is the Pareto frontier for discharge of 450–150 cms and "250 cms" is the Pareto frontier for discharge of 250–450 cms. Each line is coloured by temperature. The black box represents the optimal strategy

TABLE 1 Management recommendations to balance Sacramento River winter-run Chinook and green sturgeon. Management recommendation temperature and discharge is based on release from Keswick Dam

Species present	Months	Management recommendation	Impact	Reference
Green sturgeon	April–May	As warm as possible, low discharge	Improve sturgeon body condition, preserve cold water for winter-run	Statistical submodel in
Green sturgeon Winter-run chinook	June–early July	11.5°C, low discharge	Optimize metrics for both species	Multi-objective optimization model
Winter-run chinook	Early July–November	11.5°C or below, high discharge	Winter-run egg survival and meet water transfers	Martin et al. (2017)

years from 2000 to 2015. Winter-run temperatures were possible to release in 75% of years, water user discharge was possible in 94% of years and larval green sturgeon releases were possible in 94% of years if discharge is the only criteria used. Cool water for winter-run was the most challenging objective because drought conditions resulted in low reservoir storage and high air temperatures. Global warming will continue to alter air temperature and precipitation patterns (Alexander et al., 2006), which may decrease the probability that the cold-water winter-run objective is met. While difficult to manage, these factors help set reasonable targets for water users, cold-water and warm-water species in this temperate river.

Our results show that changes in management could benefit green sturgeon while maintaining conditions for winter-run and water users, yet there are several challenges that remain. Green sturgeon display 'sweepstakes' reproduction (Hedgecock & Pudovkin, 2011) and experience massive early life stage mortality, which is likely impacted by more environmental factors than the temperature and discharge parameters we analysed. Other important factors not considered in this analysis include food availability and predation

(Poletto et al., 2018, S. Baird personal communication), which could be indirectly impacted by other environmental variables such as water quality and substrate type. The optimal solution is to manage water temperatures up to the threshold for winter-run, so errors in the threshold model could lead to errors in this optimization. The reservoir model algorithm assumed that TCD gates could be adjusted daily, which rarely occurs. The reservoir simulations were also run independently from year to year and did not account for the propagating effects associated with the proposed discharge and temperature management scenarios across years. Nonetheless, our results show that it is possible to design dam releases to simultaneously support warm- and cold-water species and water users in all but the most extreme drought years.

Our approach to developing an optimal dam release scenario can be extended to other ecosystems where the environment can be manipulated to provide anthropogenic resources while making habitat for multiple species. Potential applications beyond environmental flows include the management of ESA-listed species in timber harvest regions (Nalle, Montgomery, Arthur, Polasky, & Schumaker, 2004), and seagrass ecosystem restoration amidst oyster bed aquaculture (Dumbauld, Ruesink, & Rumrill, 2009). However, few systems exist where the environment can be engineered as completely as a dam controls river temperature and discharge. There are many methods for controlling dam release temperature (Sherman, 2000), and the challenge for managers thus becomes identifying species-specific (or even population-specific) thermal and discharge requirements (Olden & Naiman, 2010; Poff et al., 1997). By analysing three objectives, our model suggests that the main water management conflict in this system is between low discharge, required by larval green sturgeon and high discharge, demanded by downstream water users. The dilemma of managing for multiple imperiled species is likely to become more common in the future, as the number of species at risk of extinction continues to increase (Chapin et al., 2000). In these circumstances, optimization models are an effective tool to evaluate trade-offs in management (Horne et al., 2017; Polasky et al., 2005). Our results show that balancing the needs of multiple species and water users in this highly altered ecosystem can be achieved in most years.

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AUTHORS' CONTRIBUTIONS

L.J.Z. and M.E.D contributed ideas, data generation, data analysis and manuscript preparation. E.M.D and E.P.P contributed ideas, manuscript preparation and funding.

DATA AVAILABILITY STATEMENT

Data available via the Dryad Digital Repository. https://doi.org/10.5061/dryad.898ks73 (Zarri, Danner, Daniels, & Palkovacs, 2019).

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SUPPORTING INFORMATION

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