**Title**
Balancing management of listed salmon, sturgeon, and water users in the Sacramento River



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**Publication Date**
2018

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA

SANTA CRUZ

**Balancing management of listed salmon, sturgeon, and water users in the Sacramento River**

A thesis submitted in partial satisfaction
of the requirements for the degree of

MASTER OF ARTS

in

ECOLOGY AND EVOLUTIONARY BIOLOGY

by

**Liam J. Zarri**

June 2018

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## Table of Contents

## ABSTRACT

**Balancing management of listed salmon, sturgeon, and water users in the Sacramento River**

**by**

**Liam Zarri**

Dams have been built on most of the world's large rivers, making the management of environmental flows crucial for meeting the needs of humans and wildlife. Current water management in the mainstem Sacramento River below Keswick Dam focuses on maintaining optimal conditions for early life stages of endangered winter-run Chinook salmon (*Oncorhynchus tshawytscha*) and providing discharge to support downstream water use. We found that the low temperature and high discharge flows may negatively impact condition of threatened green sturgeon (*Acipenser medirostris*) larvae rearing in this region. We developed a multi-object optimization model which identified optimal releases of 11.5°C and 150 CMS to balance the three objectives. Reservoir levels required to meet this optimal management strategy occurred in 80% of the last 20 years. This proposed management strategy shifts to multi-object management while meeting downstream water requirements and could be used as a model to provide environmental flows in other impounded rivers.

## ACKNOWLEDGEMENTS

We thank John Carlos Garza and Bill Poytress for providing field-collected larval green sturgeon samples. Miles Daniels provided analysis support and ran Shasta reservoir models. Ben Martin and Steve Munch provided advice on the multi-object optimization model. Pete Raimondi, Megan Sabal, Ben Wasserman, Simone Des Roches, and Celia Symons provided helpful comments on drafts of the manuscript. Funding was provided by the NOAA Cooperative Institute for Marine Ecosystems and Climate and the US Bureau of Reclamation.

## INTRODUCTION

Dams impound most large rivers in the world today, and in some cases water releases are managed to meet downstream human and wildlife needs. However, different environmental requirements of sympatric endangered species can be an obstacle to effective management. Species-based management strategies for one species can inadvertently harm other co-occurring species (Thirgood et al. 2000) especially if ecosystem impacts of the management strategy are not assessed (Barrows et al. 2005). In cases where multiple species are the target of conservation efforts, ecosystem management has been shown to be an effective alternative to single-species conservation plans (Poff et al. 1997, Poiani et al. 2000; but see Vira & Adams 2009). Both river temperature (Vannote et al. 1980, Jobling, 1981, Coutant, 1999) and discharge (Poff & Zimmerman 2010) play crucial roles in shaping species distribution and abundance, and conservation plans can be implemented using dam releases (Olden & Naiman 2010) which modify discharge and/or temperature to sustain environmental flows (Brisbane Declaration 2007, Richter & Thomas 2007). Thus, environmental flows can be developed using a suite of 'focal species' in a multi-species management plan as defined by Lambeck (1997). However, these ecological uses are often at odds with anthropogenic uses of water, such as municipalities and agriculture. These compounded ecological and anthropogenic water requirements become codified into law when species are endangered, resulting in state or federal management targets. This is the case for the Sacramento River, which provides 35% of California's water supply and contains unique genetic and life history diversity for several anadromous fish species (Grantham et al. 2017) listed on the endangered species act (ESA).

The spawning grounds of two ESA-listed species, endangered Sacramento River winter-run Chinook (SRWRC) salmon (*Oncorhynchus tshawytscha*) and threatened green sturgeon (*Acipenser medirostris*), did not historically overlap in the Sacramento River. Before the construction of Shasta Dam, SRWRC spawned in high-elevation cold habitat (Fisher 1994) while green sturgeon spawning habitat suitability indicates suitable habitat in the mainstem above Shasta Dam (Mora et al. 2009). Both species are now forced to spawn in the mainstem below the dam (Figure 1), representing a 100% loss of spawning habitat for SRWRC (Fisher 1994) and a significant loss of spawning habitat for green sturgeon (Mora et al. 2009); this displacement has contributed to the ESA-listing of both species. Current management chills as much of the river as possible for SRWRC egg survival using a temperature control device, which allows selective release of cold hypolimnetic or warm epilimnetic flows from Shasta Dam. This management strategy results in a colder mainstem Sacramento River than before the dam was built (Figure 2) and overlaps with current green sturgeon spawning grounds. However, experimental studies show that green sturgeon are adapted to warmer temperatures (Mayfield & Cech 2004, Van Eenennaam et al. 2005), suggesting that cold releases for SRWRC may be negatively impacting green sturgeon.

During the temperature management season for SRWRC (May – November), Shasta Dam releases are aimed at maintaining cold temperatures for incubating eggs while delivering adequate discharge for downstream water users. Current management seeks to set river temperature at the experimentally derived 13.3°C for SRWRC egg survival (USFWS, 1999) from May to November, but recent work has indicated that a threshold of 12°C may better represent field conditions (Martin et al. 2017). However, the impact of dam release temperature or discharge on larval green sturgeon in the wild has not yet been assessed. Given the presence of green sturgeon (from mid-April to July) and new temperature information for SRWRC (which begin laying redds, or egg nests, as early as late April, Figure 3b), it is important to assess whether cold water releases starting in May are an optimal management strategy for both species. River discharge must be considered as well, as it provides discharge for agriculture, municipal water transfers, and prevention of salinity intrusion to the San Francisco Delta (MacDiarmid, 1975). Downstream water users require particular discharge levels and SRWRC egg survival requires particular temperature levels and discharge above certain threshold, but it is unknown what temperature and discharge levels promote larval green sturgeon health. We seek to examine the water management options for the Sacramento River to determine if it is at an optimal balance for SRWRC, green sturgeon, and downstream water users.

We use five years of green sturgeon collections and SRWRC data from 2012 and 2016 to investigate two major questions: (1) Are water temperature management targets aimed at protecting SRWRC egg development detrimental to larval green sturgeon body condition? (2) Are there dam release strategies that can optimize management of SRWRC, green sturgeon, and downstream water users? Our study includes both drought and non-drought years to encompass a range of temperature and discharge conditions. To understand tradeoffs between dam release temperature and discharge for both species, we use a multi-objective optimization model (Polasky et al. 2005, Lester et al. 2013). We constrain management scenarios to those which satisfy the discharge requirements of water users, based on historical records of discharge from the dam (Figure 3a). Multi-object optimization allows us to find optimal and management strategies and, perhaps more importantly, determine whether a management strategy is non-optimal.

## METHODS

### *Overview*

To address question 1, we used field collections of larval green sturgeon by US Fish & Wildlife service to determine whether Shasta Dam release temperature (measured in Celsius) and discharge rate (measured in cubic meters per second, or CMS) impact larval sturgeon body condition. Body condition was calculated using length-weight residuals and compared against the river temperature and discharge rate experienced through development. Multiple linear regression analyses were used to determine the best predictors of body condition and to parameterize a predictive model.

To address question 2 we compared metrics for health for both species across the 5 years of our study. We used our model of green sturgeon body condition and an adapted model of SRWRC egg survival (Martin et al. 2017) to understand each species' response to dam release temperature and discharge. These responses were then compared over a range of dam release temperature and discharge (which meet discharge requirements of downstream water users) in a multi-object optimization model, to identify an optimal management scenario across the season. Finally, we calculated the starting reservoir level required for this optimum management scenario, and then evaluated what proportion of years met this level.

*Larval green sturgeon collections*

US Fish & Wildlife Service collected larval green sturgeon as bycatch mortality from screw traps at Red Bluff Diversion Dam (RBDD from 2012 to 2016. Total length (TL) was measured at the time of capture, and samples were transported to the Southwest Fisheries Science Center of the National Marine Fisheries Service. Caudal fin tissue was removed for a genetic study for all years except 2016, so we estimated weight of fish in 2012-2015 using pre and post clipped fish in 2016 ($R2=0.98$). Samples were removed from 95% ethanol storage vials and blotted dry. Weight was measured to the nearest 0.0001 grams, and scale standard deviation of weight was estimated at 3.15% ($n=10$). No precise technique has yet been developed to age green larval sturgeon; however, fish captured at RBDD were primarily 24-34 mm TL, suggesting they are 2 weeks post hatch (USBR 2008). To avoid the confounding effect of age, we constrained our study to 24mm-34mm TL fish.

*Question 1: Are water temperature management targets aimed at protecting SRWRC egg development detrimental to larval green sturgeon body condition?*

We estimated temperature and discharge at daily intervals using RAFT, a physical model developed by the National Marine Fisheries Service. RAFT estimates sub-hourly temperature and discharge for every kilometer of the Sacramento River downstream from Keswick Dam (Pike et al. 2013, Daniels et al. 2018). Drought years resulted in a small number (n = 8) of fish which exposed to exceptionally warm development temperatures, and these outliers were removed from further analysis. River temperature and discharge rate through development were calculated for each individual green sturgeon then compared against condition residuals.

We assessed the impact of river temperature and discharge rate on sturgeon condition factor, an indicator of fish energy stores and health (Le Cren, 1951, Sutton et al. 2000, Craig et al. 2005). Larval green sturgeon drift from the hatching site downstream, so we do not have data on the precise development location. Instead, we averaged daily temperature and discharge between the upstream spawning region (as identified by Poytress et al. 2009) and RBDD. The mean and standard deviation of each environmental metric was then calculated for each fish for the 2 weeks before capture. We calculated condition factor for each fish using the residuals of a nonlinear regression. First, we fit a nonlinear regression analysis of log(weight) by log(total length) to estimate a and b parameters in the following:

$$W = a \cdot TL^b$$

where W is fish weight, TL is total length, and a and b are constants. Then, we took the residuals of expected to actual weight as the condition factor. Positive condition factor indicates that the fish was heavier than expected for a given length, while a negative condition factor indicated the fish was lighter. Condition factor was normally distributed and was used as the response variable in mixed linear models with river temperature, discharge rate, and year as random effect. The best fit model, as measured by corrected Akaike Information Criterion (AICc, Hurvich & Tsai 1989), was used to parameterize a predictive model of the response of larval green sturgeon body condition to river environment.

*Question 2: Are there dam release strategies that can optimize management of SRWRC, green sturgeon, and downstream water users?*

SRWRC egg to fry survival was calculated as the proportion of number of eggs estimated in USFWS redd counts to the number of surviving fry estimated using screw trap counts at Red Bluff Diversion Dam, approximately 90km downstream (NMFS, 2013-2017). Green sturgeon body condition, which was used because there is not data on egg production, was averaged for each year. Body condition is an indicator of fish fat reserves and health (Le Cren, 1951), and has been associated with health of shovelnose sturgeon (Kappenman et al. 2009). Temperature and discharge were modeled using the River Assessment for Forecasting Temperature (RAFT, Pike et al. 2013, Daniels et al. 2018) and averaged for each year between April and

November when early life stages of green sturgeon and/or SRWRC were present in the study area.

To assess tradeoffs between management for SRWRC and green sturgeon, we developed a multi-object optimization model to understand the impact of temperature and discharge on both species. The statistical submodels assessed the impact of river environment in the area where SRWRC and green sturgeon develop, so we first calculated how dam release temperature and discharge impact each species' environment. Both submodels assume a constant temperature and discharge through development. Our SRWRC model came from Martin et al. (2017), which identified the impact of egg development temperature on daily instantaneous mortality rate. This is an additive model across the egg incubation period, given by:

$$h = \sum_{i=0}^{d} b_t \left( T_i - T_{crit} \right)$$

where ***h*** is predicted daily mortality rate, $T_{crit}$ is the temperature threshold above which mortality begins to increase and $T_i$ is the daily temperature for day *i* through eggs hatch at day *d*. $b_t$ is the slope of mortality above $T_{crit}$, and these are estimated in Martin *et al* 2017 as 0.024 and 12°C, respectively. Martin et al. 2017 estimated *d*, the temperature dependent maturation function, as 0.001044 ($°C^{-1}$ $d^{-1}$) * Ti + 0.00056 ($d^{-1}$), where SRWRC emerge when this value exceeds 1. Due to lack of supporting data, our model assumed no impact of discharge on egg survival. Low discharges can cause egg mortality if redds dewater, but these low flows rarely occur during the summer when downstream water demands are high. We developed the green sturgeon submodel (See *Question 1*) to predict body condition over the ~14 days until they pass RBDD:

$$K = \sum_{i=0}^{14} b_t \cdot T_i + b_d \cdot D_i + x$$

where K is predicted body condition, $b_t$ is the estimated coefficient for the effect of daily temperature $T_i$, $b_d$ is the estimated coefficient for daily discharge $D_i$, and x is the intercept.

We ran the statistical submodels over a range of dam release temperatures and discharges observed from 2012-2016 to plot a multi-object optimization model (R Statistical Language 2017, version 3.4.2). This graphical approach assumes no weighting or difference in the response between either objective, which allows the user to make a decision based on the importance of either axis. Each management strategy is plotted with x = response of objective 1 and y = response of objective 2, and a pareto front is drawn on the outer edge of the point cloud. A pareto front containing a point on the highest values of both objectives indicates there is an optimal strategy, while a straight or curved line indicates that tradeoffs are required. Dam release discharge is limited by requirements of downstream water users, so we constrained the monthly discharge rate to the 25$^{th}$ and 75$^{th}$ percentile of release from 1996-2016 (Figure 3a). Dam release temperature is also limited by the available volume of cold water, so we constrained the monthly temperatures to 10$^{th}$ and 90$^{th}$ percentiles of release from 1996-2016 (Figure 3a). Finally, we calculated the required amount of water at the beginning of the season to undertake this optimal management strategy, and, using starting reservoir levels from 1996-2016, calculated what proportion of years met this level. Reservoir volume and total cold water volume are positively correlated, so this model does not take cold water volume into account.

## RESULTS

*Question 1: Are water temperature management targets aimed at protecting SRWRC egg development detrimental to larval green sturgeon body condition?*

Water temperature and discharge rate during development had a significant impact on larval green sturgeon condition factor (Figure 4). Development temperature and discharge in the Sacramento River were somewhat colinear, but within acceptable limits (value of 3, as estimated by variance inflation factor (Zuur et al. 2007)). Two-week measurements in green sturgeon rearing grounds showed a variance inflation factor of 1.53. Variance in temperature and discharge, measured using standard deviation from the mean, were not significant predictors of green sturgeon condition factor and were excluded from further analysis.

Environmental conditions at RBDD had a significant impact on larval green sturgeon condition factor (Figure 4). Condition factor increased with temperature (linear regression: $p < 0.001$, $r^2 = 0.07$, F-statistic = 19.21, 95% confidence interval of slope = 0.13-0.24), and decreased with discharge (linear regression: $p < 0.001$, $r^2 = 0.13$, F-statistic = 39.63, 95% confidence interval of slope = -0.002 - -0.0009). Model fit using linear regression showed temperature and discharge, and discharge alone, to be the best fit models (Table 1). To determine which model was best between these two, we used resampling (n = 1000) with adjusted $r^2$ as the determining factor. This approach revealed temperature and discharge to be the best predictor (Welch's two-sample t-test, t = -2.388, p = 0.017). We use the best fit model to parameterize the following equation:

$$K_i = \sum_{i=0}^{14} b_t \cdot T_i + b_d \cdot D_i + x$$

where $K_i$ is the daily instantaneous green sturgeon condition, $b_t$ is the estimated parameters for effect of daily temperature $T_i$, $b_d$ is the estimated parameter for daily discharge $D_i$, and x is the intercept. This model was then used to predict sturgeon daily body condition over the range of river temperature and discharge observed in field collections (Figure 5a).

*Question 2: Are there dam release strategies that can optimize management of SRWRC, green sturgeon, and downstream water users?*

First, we examined metrics of health for both species from field data across the 5 years of the study (Figure 6). The cold, high discharge years of 2012 and 2013 had high SRWRC egg survival and poor green sturgeon condition. The warm, low flow drought years of 2014 and 2015 had low SRWRC egg survival and higher green sturgeon condition. 2016 was a unique year in that both winter-run and green sturgeon biological metrics were good. These 5 years of data provide historical evidence of dam releases that negatively impacted green sturgeon (2012, 2013), negatively impacted SRWRC (2014, 2015), and positively impacted both species

(2016). Thus, the management plan implemented in 2016 provides promising evidence that optimal flow management is possible.

We then combined the two statistical submodels in a multi-object optimization model, which indicated that there is an optimal management strategy. We adapted the submodels to dam releases by calculating how much temperature and discharge changes from the dam downstream. During the summer and fall, the river warms as it moves downstream from Keswick Dam, increasing 0.46°C ($\sigma$ = 0.06°C) to the bottom of winter-run red locations and 2.20°C ($\sigma$ = 0.52°C) to green sturgeon spawning locations. Discharge does not change dramatically until a large diversion at Red Bluff. The submodels predict how a range of dam releases observed through the season (10°C - 13°C, 150CMS – 450 CMS) alter green sturgeon body condition and SRWRC egg to fry survival (Figure 5a). Green sturgeon body condition was positive at warm, low discharge dam releases, while SRWRC egg to fry survival was higher at cold temperatures. The multi-object optimization model combined the predicted SRWRC egg to fry mortality across the developmental period and green sturgeon body condition across the 14-day development period (x-axis and y-axis, respectively, Figure 5b). It is important to note that the probability of SRWRC egg mortality increases rapidly above $T_{crit}$, from zero at 11.5°C to 100% at 12°C.  Over the study period, temperature management releases were approximately 10.8°C -11.8°C while discharge releases for downstream water users were 257-323 CMS, while the optimal management flow for the three objectives is 11.5°C at 150 CMS (Figure 5b). After the green sturgeon rearing season ends in July, high discharge can be released to meet downstream demands if temperatures remain at 11.5°C to prevent SRWRC temperature-related mortality. To reach this goal through the temperature management season, the reservoir level at the beginning of February must be 305 meters elevation (analysis by Daniels et al. 2018). This level was met in 16 of the last 20 years (80%). In drought years when cold water supplies are limited, we propose that discharge be lowered during the time that green sturgeon are present to increase body condition and preserve cold flows for later in the season.

**DISCUSSION**

When managing limited resources in a regulated river, there may be tradeoffs between anthropogenic uses and the protection of multiple species. Under the current management approach for the summer/fall temperature management season, water releases from Shasta Dam are aimed at maintaining cold temperatures for endangered SRWRC egg survival, while delivering adequate discharge for downstream water users. We tested whether this approach impacts larval green sturgeon and whether there are optimal flows to balance biological metrics of SRWRC and larval green sturgeon while meeting requirements of downstream water users. We found that green sturgeon body condition is positively impacted by increasing temperature and decreasing discharge. Using results on larval green sturgeon condition in conjunction with a SRWRC egg survival model, we used multi-object optimization to identify optimal Shasta Dam release temperature and discharge. Our model indicates that optimal temperature release from Shasta Dam for SRWRC and green sturgeon is possible given the natural warming of water as it flows downstream from SRWRC 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 is primarily present in the spring while the highest agricultural water demands are during the summer. Given the temporal variation in species presence and water user requirements, we can identify environmental flows to balance SRWRC egg survival and larval green sturgeon body condition while meeting requirements of downstream water users (Table 2).

We applied our optimal management strategy to 3 case study years: 2012, 2015, and 2016 (Table 3). We found that the 2012 strategy was suboptimal because too much cold water was released while green sturgeons were present, decreasing body condition. The strategy for the drought year of 2015 was suboptimal because cold water was released in June, leaving only warm flows during the SRWRC period. Our multi-species management plan provides a solution in drought years: Release warm water at low discharge until the first winter-run redd is established, so cold water is maintained for later in the season. 2016 represents an optimal year where water managers kept discharge low in spring and released water close to 11.5°C for much of the season. The take-away from these 3 case study years is to continue management targets that were executed in 2016. Our estimated requirement of 305 meters minimum reservoir level occurred in 80% of years between 1996 and 2016, but climate change may alter how often this threshold is exceeded because of altered precipitation patterns or other phenomena.

There are several unanswered questions in this system which could lead to better management in the Sacramento River for ESA listed species. Our statistical model of the impact of temperature and discharge on green sturgeon condition could be improved by elucidating mechanistic relationships. Green sturgeon body condition is well understood for larval life stages, but it could benefit management of this species to develop green sturgeon egg-to fry survival metrics as it is done with SRWRC. It is not known how the Sacramento River food web is altered by discharge and temperature, which may impact food availability for both species. Studies of other sturgeon species found that high river discharge limits spawning success (Buckley & Kynard 1985) and unfavorable environmental conditions cause reabsorption of eggs (June 1977); spawning sturgeon are sensitive to river environment and our findings suggest that larval sturgeon body condition is impacted by river temperature and discharge.

Our approach to developing an optimal scenario for managing environmental flows in the Sacramento River can be extended to other ecosystems where vulnerable life stages of ESA-listed species overlap temporally and spatially. For example, providing habitat for ESA-listed and ecologically important species while also managing timber harvest (Nalle et al. 2004), or balancing habitat restoration in oyster bed aquaculture (Dumbauld et al. 2009). The dilemma of management for a displaced endangered species negatively impacting another ESA-listed 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 this circumstance, optimization models have been found to be an effective resource to evaluate trade-offs in management (Polasky et al. 2005, Lester et al. 2013). In acknowledging the requirements of downstream water users, we constrain the range of the multi-species management plan to those which meet historic discharge requirements for agriculture and municipal use. We find evidence that balancing all three objectives is possible and encourage the integration of other objectives for more comprehensive management in the Sacramento River.

**FIGURES**

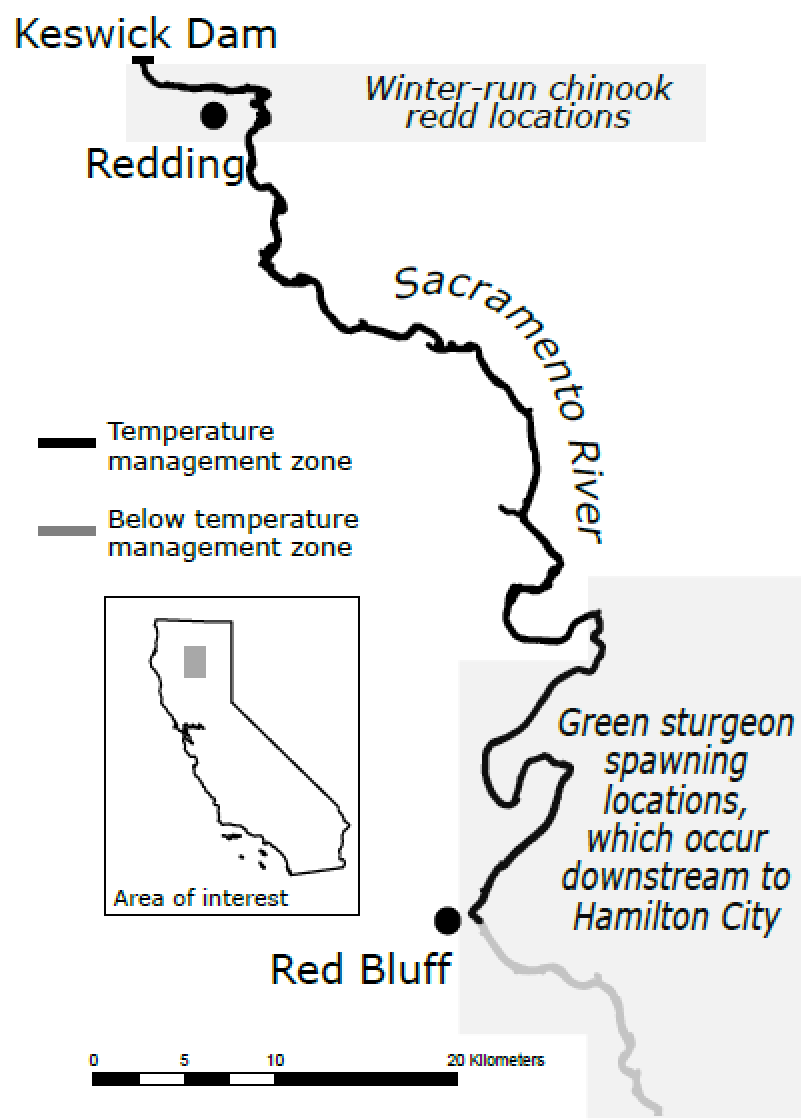


**Figure 1**. Map of the Sacramento River below Keswick Dam to Red Bluff, with river regions of Sacramento River winter-run Chinook redds, green sturgeon spawning, and temperature management

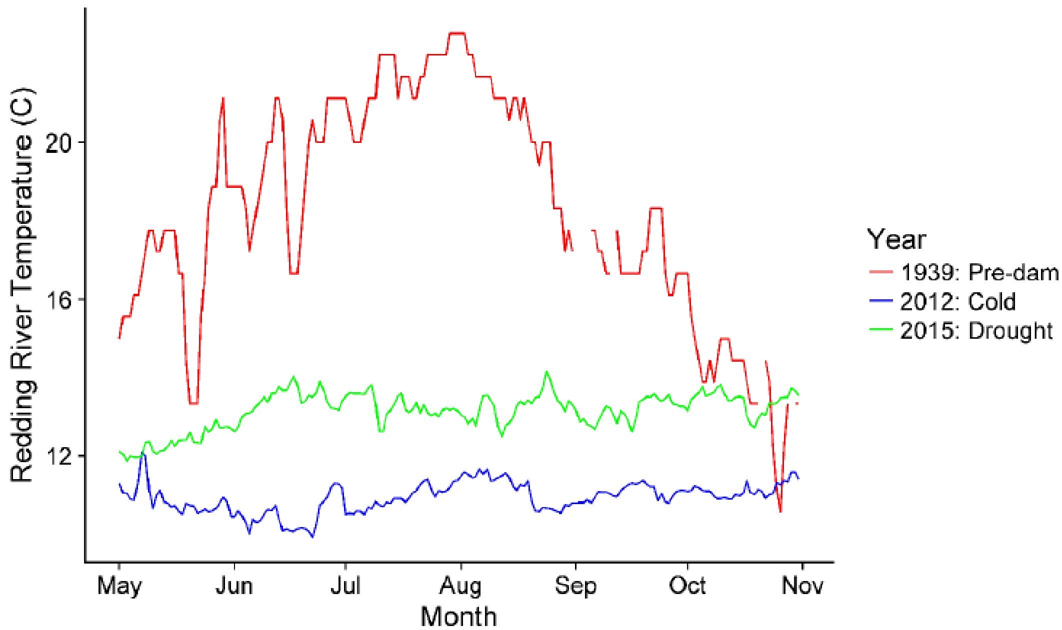


**Figure 2**. Sacramento River water temperatures at the City of Redding in 1939 before dam construction (red line), after dam construction during a normal water year (2012, blue line), after dam construction during a drought year (2015, green line). Temperature data for 2012 and 2015 are from RAFT (Pike et al. 2013, Daniels et al. 2018), and historical temperatures from Cope (1949).

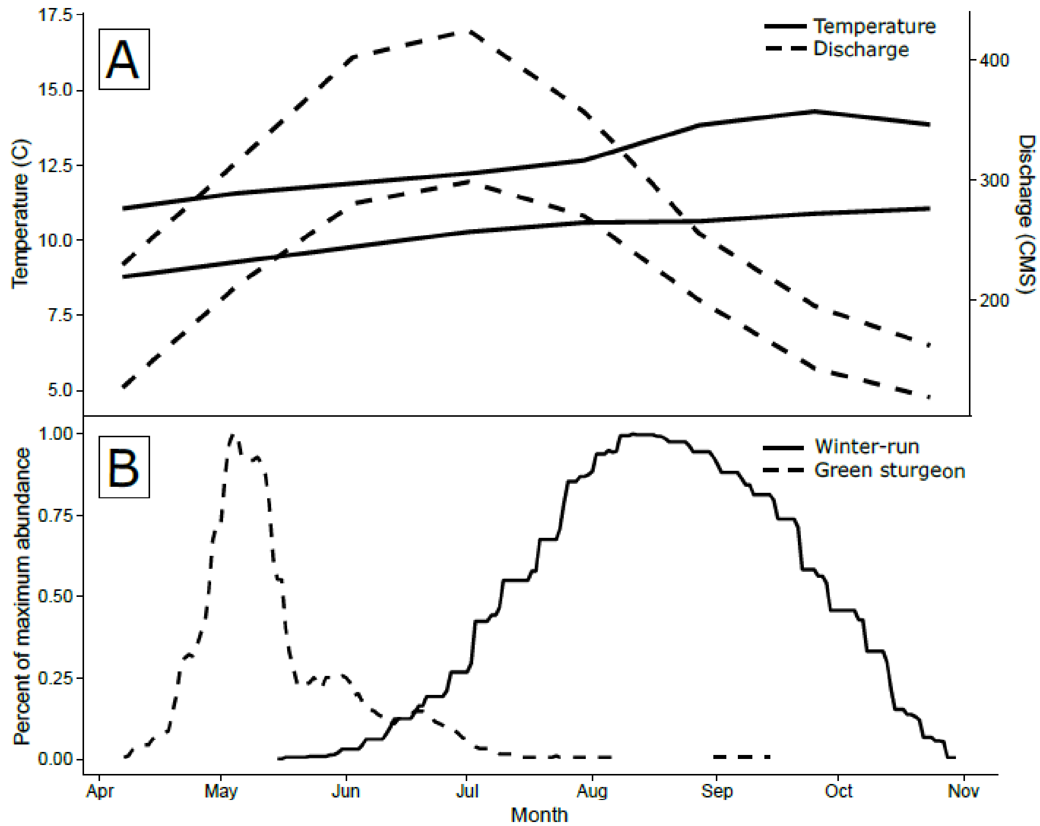


**Figure 3**. (A) Availability of temperature (10th and 90th quartiles) and discharge (25th and 75th quartiles) releases from Keswick Dam by month from 1990-2016, and (B) temporal distribution of Sacramento River winter-run Chinook eggs and green sturgeon larvae presence above RBDD.

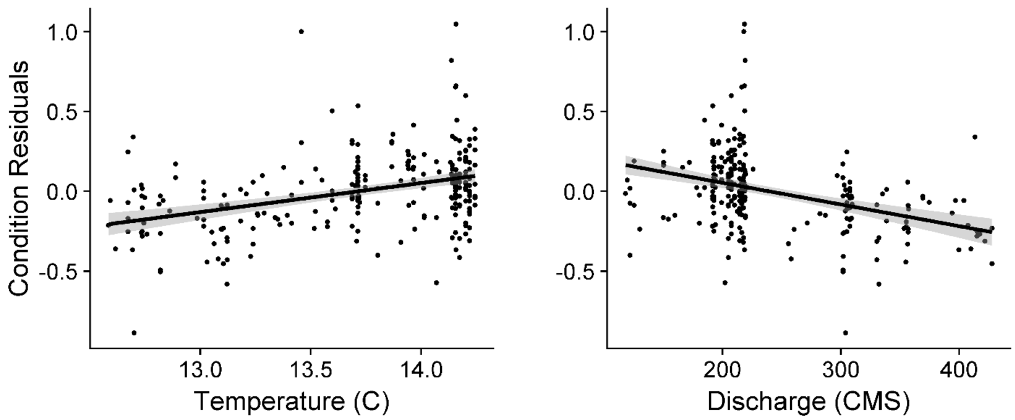


**Figure 4**. Linear regression of temperature and discharge on green sturgeon body condition residuals, with 95% confidence intervals

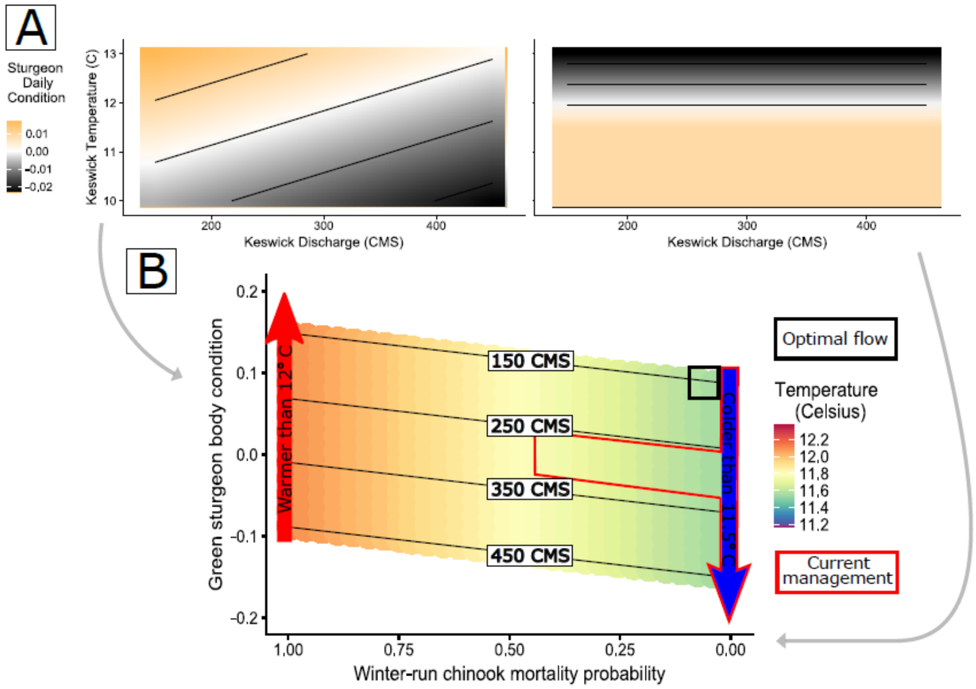


**Figure 5**. (A) Impact of Keswick Dam temperature and discharge releases on daily condition of larval green sturgeon and yearly Sacramento River winter-run Chinook egg to fry survival. (B) Multi-object optimization model generated by modeled response of Sacramento River winter-run Chinook and green sturgeon to dam release temperature and discharge. Lines represent 4 separate dam release discharge strategies while color represent dam release temperature strategies. The red shading represents the current temperature management strategy while the black shading represents the optimal strategy

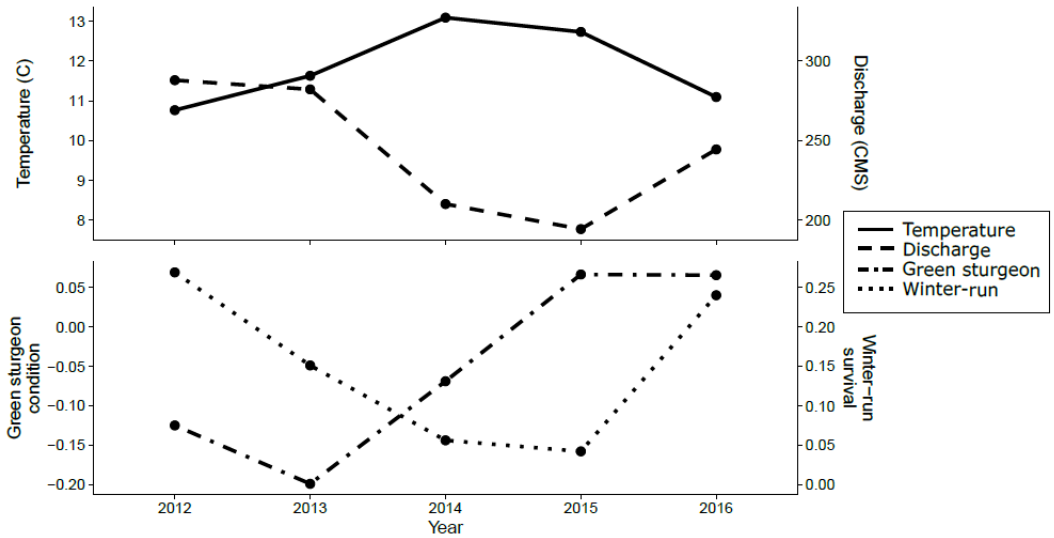


**Figure 6**. Average environment and biological response across the 5 years of this study. The top graph is mean temperature and discharge at Keswick Dam from April to November across the 5 years of this study. The bottom graph is a comparison of green sturgeon condition and Sacramento River winter-run Chinook egg to fry survival.

| **Predictors** | **Random Effect** | **df** | **logLik** | **AICc** | **ΔAICc** | **Adj. $r^2$** |
|---|---|---|---|---|---|---|
| T + D | - | 4 | 673.636 | -1339.1 | 0 | 0.17 |
| T + D | Year | 5 | 673.636 | -1337.0 | 1.9 | 0.17 |
| T * D | - | 5 | 673.600 | -1337.0 | 1.9 | 0.17 |
| T * D | Year | 6 | 673.600 | -1334.9 | 4.2 | 0.17 |
| T | - | 3 | 670.112 | -1334.1 | 5.0 | 0.15 |
| T | Year | 4 | 670.694 | -1333.2 | 5.9 | 0.15 |
| D | - | 3 | 669.533 | -1333.0 | 6.1 | 0.14 |
| D | Year | 4 | 669.81 | -1331.5 | 7.6 | 0.14 |
| - | Year | 3 | 667.487 | -1328.9 | 10.2 | 0.12 |
| - | - | 2 | 650.691 | -1297.3 | 41.8 | 0.00 |

**Table 1**. The best fit models for response variable of larval green sturgeon body condition. Interaction is indicated by '*' while additive is '+'. Predictors are temperature (T) and discharge (D).

| Species present | Months | Management recommendation | Impact |
|---|---|---|---|
| Green sturgeon | April – May | Warm, low discharge | Increase sturgeon body condition, preserve cold water for winter-run |
| Green sturgeon Winter-run chinook | June – early July | 11.5°C, low discharge | Optimize metrics for both species |
| Winter-run chinook | Early July – November | High, cold discharge | Maintain winter-run survival and meet water transfers |

**Table 2**. Proposed management phases to balance Sacramento River winter-run Chinook and green sturgeon

| Year | Metrics | Green sturgeon present | Green sturgeon and winter-run chinook present | Winter-run chinook present |
|---|---|---|---|---|
| 2012 | Salmon good<br>Sturgeon poor | Suboptimal<br>Too cold | Suboptimal<br>Too cold, high discharge | Optimal |
| 2015 | Salmon poor<br>Sturgeon good | Optimal | Suboptimal<br>Too hot | Suboptimal<br>Too hot |
| 2016 | Salmon good<br>Sturgeon good | Optimal | Optimal | Optimal |

**Table 3**. Comparison of species metrics across 3 years, with 3 distinct time periods of species presence. Filled cells indicate whether the management in each year and time period were optimal and suboptimal for the species present, and, if suboptimal, what environmental characteristics were suboptimal.

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