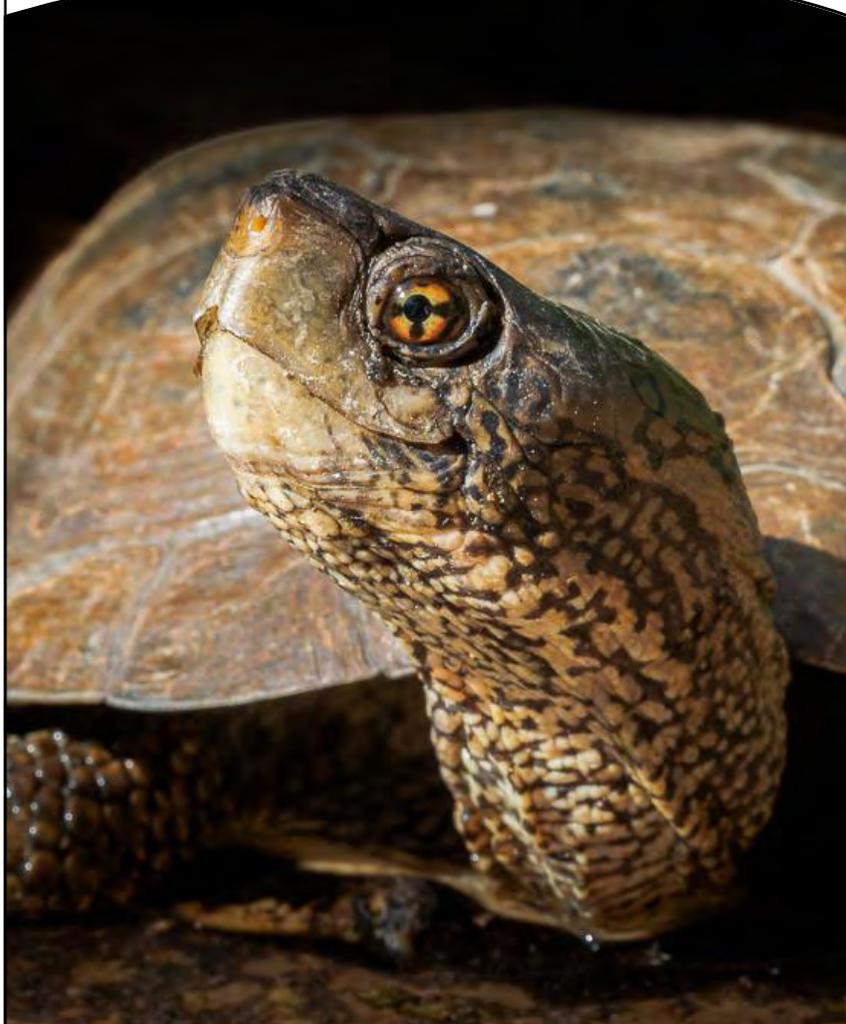


# California Fish and Wildlife JOURNAL

VOLUME 106 • FALL 2020 • NUMBER 4



*Journal for the Conservation and Management of  
California's Species and Ecosystems*

Published Quarterly by the California Department of Fish and Wildlife

STATE OF CALIFORNIA  
Gavin Newsom, *Governor*

CALIFORNIA NATURAL RESOURCES AGENCY  
Wade Crowfoot, *Secretary for Natural Resources*

FISH AND GAME COMMISSION  
Eric Sklar, *President*  
Jacque Hostler-Carmesin, *Vice President*  
Russell Burns, *Member*  
Peter S. Silva, *Member*  
Samantha Murray, *Member*

Melissa Miller-Henson, *Executive Director*

DEPARTMENT OF FISH AND WILDLIFE  
Charlton “Chuck” Bonham, *Director*

CALIFORNIA FISH AND WILDLIFE  
EDITORIAL STAFF

Ange Darnell Baker .....Editor-in-Chief  
Lorna Bernard.....Office of Communication, Education and Outreach  
Neil Clipperton, Scott Osborn, Laura Patterson, Dan Skalos,  
Katherine Miller Karen Converse, Kristin Denryter, Matt Meshiry,  
and Megan Crane ..... Wildlife Branch  
Felipe La Luz and Ken Kundargi ..... Water Branch  
Jeff Rodzen, Jeff Weaver, John Kelly, and Erica Meyers ..... Fisheries Branch  
Cherilyn Burton and Katrina Smith..... Habitat Conservation Planning Branch  
Kevin Fleming ..... Watershed Restoration Grants Branch  
Jeff Villepique, Steve Parmenter..... Inland Deserts Region  
James Ray ..... Marine Region  
David Wright and Mario Klip..... North Central Region  
Ken Lindke, Robert Sullivan ..... Northern Region  
Lauren Damon ..... Bay Delta Region  
Randy Lovell .....Aquaculture Program  
Jennifer Nguyen..... Cannabis Program

# California Fish and Wildlife

VOLUME 106

FALL 2020

NUMBER 4



Published Quarterly by

STATE OF CALIFORNIA  
CALIFORNIA NATURAL RESOURCES AGENCY  
DEPARTMENT OF FISH AND WILDLIFE

ISSN: 2689-419X (print)  
ISSN: 2689-4203 (online)

--LDA--

# California Fish and Wildlife Journal

*The California Fish and Wildlife Journal* is published quarterly by the California Department of Fish and Wildlife. It is a journal devoted to the conservation and understanding of the flora and fauna of California and surrounding areas. If its contents are reproduced elsewhere, the authors and the California Department of Fish and Wildlife would appreciate being acknowledged.

Please direct correspondence to:  
Ange Darnell Baker  
Editor-in-Chief  
*California Fish and Wildlife*  
Angela.Baker@wildlife.ca.gov



Inquiries regarding the reprinting of articles and publishing in future issues can be directed to the Subscription Manager via email at [publications@wildlife.ca.gov](mailto:publications@wildlife.ca.gov).

Alternate communication format is available upon request. If reasonable accommodation is needed, call 916-322-8911 or the California Relay (Telephone) Service for the deaf or hearing-impaired from TDD phones at 800-735-2929.

# Contents

<b>Notes from the Editor</b>	
ANGE DARNELL BAKER .....	202
<b>Validated age and growth of Barred Sand Bass within the Southern California Bight</b>	
KIMBERLY M. WALKER, KIMBERLY M. PENTTILA, ERICA T. JARVIS-MASON, AND CHARLES F. VALLE .....	205
<b>Time series modeling and forecasting of a highly regulated riverine system: implications for fisheries management</b>	
ROBERT M. SULLIVAN AND JOHN P. HILEMAN .....	221
<b>Ecology of Northwestern Pond Turtles in a Sierran Foothill Population, California</b>	
DAVID J. GERMANO.....	261
<b>Green Sturgeon (<i>Acipenser medirostris</i>) in the San Joaquin River, California: new record</b>	
SHAUN T. ROOT, ZACHARY SUTPHIN, AND TOWNS BURGESS .....	268
<b>BOOK REVIEW:</b>	
<b>Ruling the Waters: California’s Kern River, the Environment, and the Making of Western Water Law.....</b>	<b>271</b>
<b>BOOK REVIEW:</b>	
<b>The Cougar Conundrum: Sharing the World with a Successful Predator.....</b>	<b>274</b>
<b>Information for authors.....</b>	<b>279</b>
<b>Subject Matter Index for California Fish and Wildlife 106 (2020) .....</b>	<b>280</b>
<b>Author Index for California Fish and Wildlife 106 (2020).....</b>	<b>282</b>

## Notes from the Editor

The fall issue of 2020 comes a bit later than normal—our staff were consumed with the 3 special issues that we put out this year (more info on that at the end). Although not intentional, the issue seems to have a theme: water—all of the articles and one of the book reviews are about aquatic animals and water in California. The issue begins with an article by Kim Walker and her colleagues from both CDFW and the Scripps Institution of Oceanography about updated life history information—age and growth—of Barred Sand Bass. Next, Bob Sullivan and John Hileman from CDFW’s Northern Region provide an interesting use of time series modeling and forecasting of the Trinity River in northwestern California; their results provide implications for fisheries management in this area. Following the two full research articles are two notes: one by Dave Germano, from CSU-Bakersfield, about the ecology of a Sierran foothill population of northwestern pond turtles and the other a new record of Green Sturgeon in the San Joaquin River from Shaun Root and his colleagues at the Bureau of Reclamation. Lastly, the issue finishes with two book reviews: one on mountain lions and the other covering how the development of the San Joaquin Valley influenced water law in California.

Our editorial team both grew and shrank this quarter. We have *four* new Associate Editors, while one is leaving us. Erica Meyers and John Kelly join us as much-needed fisheries editors. Erica has been with the Department since 2012, working for six years in the San Joaquin River Restoration Program prior to taking a position in Fisheries Branch as the Central Valley Chinook Salmon Coordinator. In 2003, she earned her bachelor’s degree at the University of Wisconsin, Madison, studying Conservation Biology in the Wildlife Ecology department founded by Aldo Leopold. She began her career rearing whooping cranes for reintroduction at the International Crane Foundation in Baraboo, Wisconsin, before moving to California to monitor salmonid populations in the Klamath Basin for CDFW. Erica received her Master of Environmental Science and Management degree from the University of California, Santa Barbara, in 2009. Her graduate studies focused on stream ecology, river restoration, and water resources management. Erica is particularly interested in applied science, anadromous fishes, hydrology, aquatic habitats, and the pursuit of elegant solutions to complex problems. John Kelly completed his bachelor’s degree at the University of Miami, FL, in 1995 before beginning his career as a reef fish biologist with The Nature Conservancy. He earned his PhD in 2006 at the University of California, Davis, where he studied Green Sturgeon movement and orientation. His areas of expertise include fish ecophysiology and behavior, and he has particular interests in euryhaline and anadromous fishes, osmoregulation, swimming performance, metabolism, stress, and biotelemetry. Dr. Kelly conducted postdoctoral research at the USGS Conte Anadromous Fish Research Center and the University of Massachusetts, Amherst, prior to serving as a tenured Associate Professor and Marine Biology Program Coordinator at the University of New Haven, CT. After nine years, Dr. Kelly chose to leave academia to return to California and follow his passion for fish conservation and management. He joined CDFW in 2018 and now serves in Fisheries Branch as Sturgeon Coordinator.

We also gained two wildlife editors, Matt Meshriy and Megan (Mayo) Crane. Matt Meshriy is an Environmental Scientist in CDFW's Upland Game Program at the Wildlife Branch. Matt serves as a coordinator for policy and management with statewide responsibilities for upland game birds, small game, furbearing and nongame mammals. Matt holds a bachelor's degree in Ecology and Evolution and a master's degree in Animal Physiology and Behavior from San Francisco State University where his thesis work involved field investigations of the endangered giant kangaroo rat. Matt has banded spotted owls with the U.S. Forest Service and worked in California's Central Valley to lead USGS field investigations of giant garter snakes. Matt joined CDFW in his current role in 2012. Mayo Crane is a Florida native who came to California to study birds. She completed her PhD at UC Davis in Ecology, focusing on population genomics in avian systems. Currently, she is an Environmental Scientist with CDFW; she focuses on migratory upland game and runs the mourning dove banding program.

We also lost a great editor this quarter—Paul Reilly has been an AE for the Journal for many years and resigned in order to give others the chance to provide their expertise to the Journal. Paul, a Senior Environmental Scientist (Supervisor), began his career with CDFW as a Seasonal Aid in October 1975 in Menlo Park, fresh out of the University of Rhode Island's Graduate School of Oceanography, and then became a Biologist in 1976. He applied his knowledge of zooplankton by studying Dungeness crab larval dynamics, as well as Dungeness crab fish predators. In 1980 as an Associate Biologist in Santa Barbara, he led a 2-year field study of fishes and invertebrates in Little Cojo Bay, Santa Barbara County, and began the first of 20 years as a certified Department scuba diver. From 1982 to 1992 he focused on research and management for the San Francisco Bay Herring fishery, including the use of hydroacoustics for biomass estimates. In 1992, he became a Supervisor in Monterey and led a scuba and commercial passenger fishing vessel study of nearshore and shelf rocky reef fishes. In 1999 he was designated as the Department's expert on marine protected areas and for the next 7 years became immersed in the Marine Life Protection Act process, but also developed regulations for the restricted access spot prawn trap fishery and supervised his staff who were all working on projects other than marine protected areas. In 2006, Paul became the Supervisor of the Northern and Central California Finfish Research and Management Project, currently with a staff of eight. Focal species include California Halibut, Surfperches, Pacific Hagfish, White Seabass, and True Smelt. He and Travis Tanaka have aged more than 4,000 halibut otolith thin sections. Paul has continued a long-term database for beach fishing effort in Monterey County since 2007. He reviews many documents and has participated in the hiring of many Marine Region staff over the years.

We also had an excellent guest editor this issue that filled the gap we had for fish biologists before John and Erica joined our team. Claire Ingel is a Senior Environmental Scientist (Specialist) in the Native Fishes Conservation and Management program of Fisheries Branch. She earned a Bachelor of Science degree in Biological Sciences from UC-Davis and a Master of Science in Natural Resources from Cornell University. Claire has worked for CDFW for 7 years within fisheries and habitat conservation programs, and approximately two years in her current role as Statewide Coordinator for the Native Fishes Conservation and Management Program. Her experience includes aquatic and fisheries management, habitat conservation and cannabis program review and permitting, grants management and coordination, aquatic education, and drought response.

With a lot of help from our editorial staff—particularly my amazing layout editor, Lorna Bernard, the Journal published its three—first ever—special issues this year. The issues focused on the impacts of cannabis, wildfire, and recreation on fish and wildlife resources. Please check out these issues as well as our upcoming ones on the California Endangered Species Act and Human-Wildlife Interactions (<https://wildlife.ca.gov/Publications/Journal/Special-Issues>).

Ange Darnell Baker, PhD  
Editor-in-Chief  
*California Fish and Wildlife Journal*

FULL RESEARCH ARTICLE

## Validated age and growth of Barred Sand Bass within the Southern California Bight

KIMBERLY M. WALKER<sup>1</sup> \*, KIMBERLY M. PENTTILA<sup>2</sup>, ERICA T. JARVIS-MASON<sup>3</sup>, AND CHARLES F. VALLE<sup>1</sup>

<sup>1</sup> California Department of Fish and Wildlife, Marine Region, 4665 Lampson Ave., Suite C, Los Alamitos, CA 90720, USA

<sup>2</sup> California Department of Fish and Wildlife, Office of Spill Prevention and Response, 4665 Lampson Ave., Suite C, Los Alamitos, CA 90720, USA

<sup>3</sup> Scripps Institute of Oceanography, Marine Biology PhD Program, 9500 Gilman Drive, La Jolla, CA 92093, USA

\*Corresponding Author: kim.walker@wildlife.ca.gov

The recreational fishery for Barred Sand Bass (*Paralabrax nebulifer*) has recently shown declines in catch prompting a need for updating life-history attributes. The objective of this study was to provide a more extensive and current examination of Barred Sand Bass age and growth. Fish were collected from the southern California bight from 2011 to 2015. Using Akaike Information Criteria analysis we determined that the three-parameter von Bertalanffy growth model was the best fit out of the four tested models (Gompertz, Logistic, Power, and von Bertalanffy). Males grew slightly quicker than females ( $k$ , males = 0.10, females = 0.08). Males and females did not differ in length, weight, or the length-weight relationship. We also validated yearly banding of Barred Sand Bass with oxytetracycline marking of two fish in captivity for one year. Location of the first annulus was also validated with otolith diameter measurements. Finally, we compared the current study to a past 1990's study and observed different growth parameters. The growth difference after thirty years showed that possible fishing pressure and environmental factors might have influenced changes in growth. This study provides current information on age, growth over time and, otolith morphometrics, for Barred Sand Bass.

**Key words:** age estimation, age validation, Barred Sand Bass; growth; otolith, *Paralabrax nebulifer*

---

Barred Sand Bass (*Paralabrax nebulifer*) range from Central California to Baja California (Miller and Lea 1972) and can be found at depths up to 183 m (Eschmeyer and Herald

1983). Barred Sand Bass has been a popular sportfish in southern California since the early 1900s (Collyer 1949) and caught commercially until 1953 when commercial fishing of Barred Sand Bass was prohibited in California. They are most often targeted during summer months when they form large spawning aggregations (Love et al. 1996; Allen and Hovey 2001; Jarvis et al. 2010). Barred Sand Bass along with its congener Kelp Bass (*Paralabrax clathratus*) are held in high esteem by recreational anglers in southern California and together the two fisheries earned 2.9 billion dollars in 2015 (NMFS 2017). They consistently have been in the top ten ranked fish caught in California on CPFVs (Commercial Passenger Fishing Vessels) since the late 1970s; however, overall catch of Barred Sand Bass has decreased dramatically since 2004 (Erisman et al. 2011; Jarvis et al. 2014), and in 2013 a regulation change occurred for all three *Paralabrax* species, including kelp bass and spotted sand bass. The daily bag limit decreased from ten to five fish in combination of all three species and the size limit increased from 12 to 14 inches total length. In the years after the regulation change (2014 to 2019), landings data indicate kelp bass are re-bounding while Barred Sand Bass numbers continue to decline (CDFW, unpublished data).

Determination of life history traits of marine fishes provides an increased understanding of population dynamics and sustainable fishery yields which support better management decisions (Treble et al. 2008; Zischke et al. 2013). The age of a fish is one of the most important biological factors measured, and informs researchers about recruitment, growth, and mortality (Leung and Allen 2016; McBride et al. 2008). These biological estimates are essential when managing marine fisheries, especially an overfished species like Barred Sand Bass. For example, life history traits may change over time in response to fishing pressures (Enberg et al. 2010). These changes are likely to require re-evaluation of fishery management tools that are based on specific life-history parameters (e.g., size at age). Thus, it appears prudent that age and growth rates of fishes be evaluated regularly (Ong et al. 2015; Williams et al. 2007). A study published over 30 years ago by Love et al. (1996) explored life history traits of Barred Sand Bass and included an assessment of age and growth and age and size at maturity. However, sample size for Barred Sand Bass were very limited (109 fish) and age validation was conducted using only marginal increment analysis (MIA). Currently, Barred Sand Bass are managed without sex-specific regulations. Sexes were previously determined to not differ for age and growth (Love et al. 1996). However, males and females of many species of fish grow at different rates, possibly because of resource partitioning (Enberg et al. 2010), and growth differences between sexes should be explored.

Aging of fish hard structures can prove to be quite difficult and is often subjective. Although many validating methods are available (radiochemical dating, bomb carbon dating for long-lived fishes, tag-recapture, and MIA to ensure aging accuracy, there are also many roadblocks enlisting these methodologies (time constraints, cost, and utility in the case of MIA). Alternative ways to assess individual ages of fish would be beneficial and should be explored within the aging community. One possible method for estimating fish ages outside of traditional methods (band pair reading of hard parts and scales) is assessing morphometrics of otoliths. Otolith morphometrics (width, thickness, length and mass) may be a good predictor of fish age (Doering-Arjes et al. 2008; Matic-Skoko et al. 2011; Lepak et al. 2012) and the cost and time spent on this method is relatively low.

When evaluating age and growth of fish species, the von Bertalanffy growth model (VBGM) is most often chosen for both sex-specific and for non-sex-specific growth models, with the assumption that this single model will describe growth best. Often, using the von Bertalanffy model *a priori* has been found to poorly describe growth, with negative

results on the fishery (Katsanevakis and Maravelias 2008). Because of this, it is important to evaluate more than one growth model to determine which best fits the available data; other common models used to assess length at age of fish include Gompertz, Power, and Logistic (Williams et al. 2012).

The objective of this study was to provide a more extensive and current examination of Barred Sand Bass age and growth by: 1) aging a large number of otoliths from both males and females; 2) validating annual periodicity of the observed growth pattern; 3) determining the relationship between otolith morphometrics and Barred Sand Bass age; 4) determining the model that best describes Barred Sand Bass growth; and 5) comparing the present models to the past study and its implications for current management of the Barred Sand Bass fishery.

## METHODS

### Sample collection and length-weight relationship

We collected Barred Sand Bass from 2011 to 2015 in coastal waters from Santa Barbara County to Orange County on predominantly sandy substrate and patch reef habitat using a variety of methods: 1) spearfishing on SCUBA, hook and line, and fish traps, 2) Los Angeles County Sanitation District's Ocean Monitoring hook and line surveys, and 3) donations from anglers on CPFVs. Fish were measured for total length (mm) and whole weight (mg) ( $n = 736$ ) and sexed by macroscopic examination of gonads. We were unable to collect gonads from all fish, so some individuals were left as unsexed. We extracted and cleaned both right and left sagittal otoliths from all usable fish. After otoliths were cleaned with deionized water and air-dried, they were placed in gelatin capsules until further processing could occur. We fit the Barred Sand Bass data to a length-weight model. The logarithmic transformation of the two-parameter power function, was used where  $W$  is whole body weight,  $TL$  is total length, and the parameters  $a$  and  $b$  are estimated using least square linear regression. Length and weight data were log-transformed to linearize the length-weight model. Homogeneity of slopes for length versus weight were compared between sexes with analysis of covariance (ANCOVA).

### Otolith processing

We selected one otolith from each pair at random and marked at the nucleus, epoxied dorsally/ventrally onto thick paper labeling tags, and cured for 24 hours. Otoliths were cut along the transverse plane through the marked nucleus with a Buehler ISOMET low speed saw using two NORTON Superabrasive Diamond Grinding Wheels set 0.3 to 0.5 mm apart. Otolith wafers were then checked for the least marred side and then affixed that side down with Cytoseal™ 60 adhesive. The slides cured for an additional 24 hours. We wet polished otolith wafers using 600 grit waterproof sandpaper and deionized water with frequent checks under the stereo microscope for the best view of bands to prevent over polishing and diminishing the banding pattern.

### Otolith reading/aging

Attempts to read all ( $n = 736$ ) otoliths were made by two readers from a live image that was projected onto a TV screen using a Sony Handycam HDR-SR7 Digital HD Video

Camera Recorder attached to a compound microscope under low magnification (4x). We aged otoliths twice on two separate occasions by each reader (= four assigned ages per otolith) no less than two weeks and no more than four weeks apart. We counted the combination of an opaque and translucent band (annulus) as one whole year of growth. A band is defined as a distinct color change on the otolith; the translucent band is clear and the opaque band is white under the transmitted light of a compound microscope (Beamish and McFarlane 1983; Campana and Neilson 1985). We assigned final ages from the total number of counted annuli. Otoliths that were given the same age three out of four times were considered aged and were not assessed again. If an age was not agreed upon three out of four times, then the readers observed the otolith together and attempted to come to an agreement for an age of the fish. Otoliths that were deemed unreadable, or when the readers could not agree upon an age, were not included in the final analysis. The precision of age estimates between readers was calculated with Chang's coefficient of variation (CV) (Chang 1982). Equation is as follows:

$$CV = \frac{\sqrt{\frac{\sum_{i=1}^N (X_{ij} - X_j)^2}{N - 1}}}{X_j} * 100\%$$

### Otolith morphometrics

We obtained measurements for 608 otoliths; the remaining otoliths were missing or damaged in some way and not used in the analyses. Otoliths were measured for mass (gram,g) and length (millimeter, mm) to establish a possible relationship with fish age. Mass was measured with an analytical balance to the 0.0001 g. The length of the whole otolith was measured with calipers to the 0.01 mm, from the longest axis along the anterior and posterior surface of the otolith. Initially, thickness and width were also measured (n = 24) but preliminary regression analysis showed them to be poor potential predictors for age, ( $r^2 = 0.41$  and  $0.53$ , respectively) so these measurements were not obtained for all otoliths. A random otolith of the pair was then chosen and the relationship of mass and length with age was determined through linear regression.

### Validation of annual periodicity and edge analysis

The annual periodicity of banding in Barred Sand Bass was evaluated by oxytetracycline (OTC) marking of live fish. To confirm that Barred Sand Bass produce two distinct bands per year, we chemically marked one opaque (white band) and one translucent (clear band) of two adult Barred Sand Bass with OTC by injection. Two adult fish measuring 334- and 349-mm total length caught in Orange County at the same general area as most fish aged in this study were injected in the dorsal muscle with 0.2 to 0.3 mL of OTC. The fish were kept in outside aquaria pens (2013 January to 2014 January) at California State University, Long Beach, then sacrificed for otolith removal after one year. Otoliths were read with an Olympus BX51 microscope under ultraviolet light, and images were taken with an attached digital camera Olympus camera. A green fluorescing band across the face of the otolith indicated the location of the OTC mark. Images were also taken under transmitted light and compared with the fluorescent otolith image so that the matched bands could be visualized. Together, the opaque and translucent banding after the OTC mark and up to the leading edge of the otolith were counted as one full year of growth.

We also performed an edge analysis by recording the growing edge (margin zone) of all otoliths as either opaque or translucent in relation to the fish's month of capture to determine the seasonality of the banding pattern within the year. Although edge analysis is not as reliable a technique for age validation as an OTC marking because light refraction and thinning of the otolith edge may cause misinterpretation (Campana 2001), edge analysis was used to reaffirm annual periodicity of banding.

The first-year annulus was validated by taking measurements of young-of-the-year otolith diameters from fish collected in October to December. We captured images of ten otoliths with a Sony Handycam Digital HD Video Camera Recorder (HDR-SR7) and digitized into ImageJ (version 1x) (Schneider et al. 2012). A digital micrometer within the program was calibrated using an image of a calibration slide. The images were then measured across the otoliths' diameter with the add-in, ObjectJ. We created a regression plot of otolith diameter-total fish length to determine the relationship between the two measurements. The modal total length (mm) of the young-of-the-year measurements was inserted into the young-of-the-year length-otolith diameter regression and the regression line was used to estimate the diameter of the first year annulus.

### Growth curve determination and historical comparison

We evaluated four different models that are commonly used to describe fish growth for males, females and the sexes combined. We included smaller unsexed juvenile fish ( $n = 21$ , TL < 205 mm) in all models to increase an accurate estimate of the parameters (Craig 1999). The sexes combined model also included an additional 100 fish of larger sizes but unknown sex. The model equations are as follows: 3-parameter Gompertz =  $L_{\infty} [\exp(-\exp(-k * (t - t_0)))]$ , Logistic =  $L_{\infty} / [1 + \exp(-k(t - t_0))]$ , 2-parameter Power =  $a * (t^b)$ , and 3-parameter von Bertalanffy =  $L_{\infty} [1 - e^{-K(t-t_0)}]$ . Parameters are defined as follows for all equations:  $L_{\infty}$  maximum asymptotic length,  $k$  = relative growth rate,  $t$  = age of fish, and  $t_0$  = theoretical age at time that length is zero, and  $a$  and  $b$  = describe the shape of the curve with no biological meaning. The models were compared using Akaike Information Criterion (AIC) to determine which model fitted the data best; the lowest AIC being the better fit model (Katsanevakis and Maravelias 2008).

We determined if growth was equal between males and females with a family of six nested models. We used planned contrasts to compare all combinations of the VBGF parameters to a general model. Separate parameters were estimated between groups (sexes) with analysis of variance.

The observable change in age and growth over time was evaluated by comparing parameters from Love et al. (1996) to the current study. We did not have access to the raw historic data, so no statistical analysis was conducted, and parameters were compared qualitatively.

All data analysis was conducted in R package v3.3.2 (R Core Team, 2017) unless otherwise noted.

## RESULTS

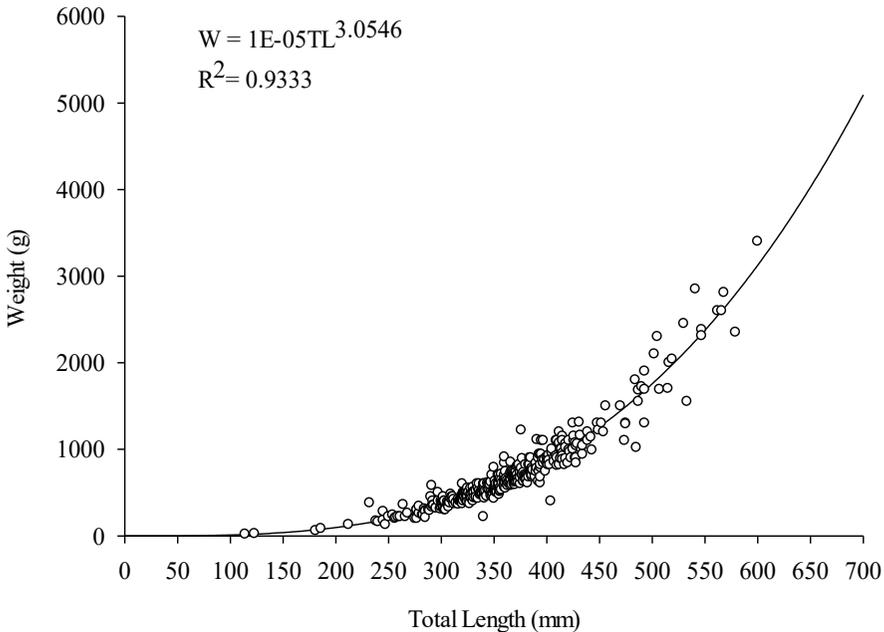
### Sample collection and length-weight relationship

We prepared 736 Barred Sand Bass otoliths for aging. Of the 736 fish assigned ages, 370 were female, 245 were male, and 121 were of unknown sex. The male: female ratio was

1:1.5 and was significantly different from a 1:1 expected ratio (Chi-Square analysis;  $\chi^2 = 25.407$ ,  $d.f = 1$ ,  $P < 0.001$ ). The total length (TL) of female Barred Sand Bass ranged from 245 to 600 mm and males from 146 to 593 mm TL. The total length of fish with unknown sex ranged from 117 - 566 mm. The total body weight for females ranged from 180 to 3400 g and 220 to 2310 g for males. There was no significant difference of distribution between male and female total length (mm) or total body weight (g) (two-sample Kolmogorov-Smirnov test,  $D(615) = 0.06442$ ,  $P = 0.5734$ , and  $D(381) = 0.11271$ ,  $P = 0.1993$ , respectively). The length-weight parameters were estimated to be  $a = -4.5935$  and  $b = 2.8868$  for males,  $a = -5.1121$  and  $b = 3.0951$  for females, and  $a = -5.0147$  and  $b = 3.0546$  for sexes combined (Table 1). Analysis of covariance for length-weight relationship of males and females were found to not have significantly different slopes (ANCOVA,  $P = 0.9904$ ) and were pooled together for fitting of the power curve. The pooled data showed a strong relationship ( $R^2 = 0.9320$ ) between length and weight (Table 1, Figure 1).

**Table 1.** Barred Sand Bass length-weight parameters estimated from the two-parameter power function,  $W = aTL^b$ . Where  $W$  is log-weight and  $TL$  is log-length.

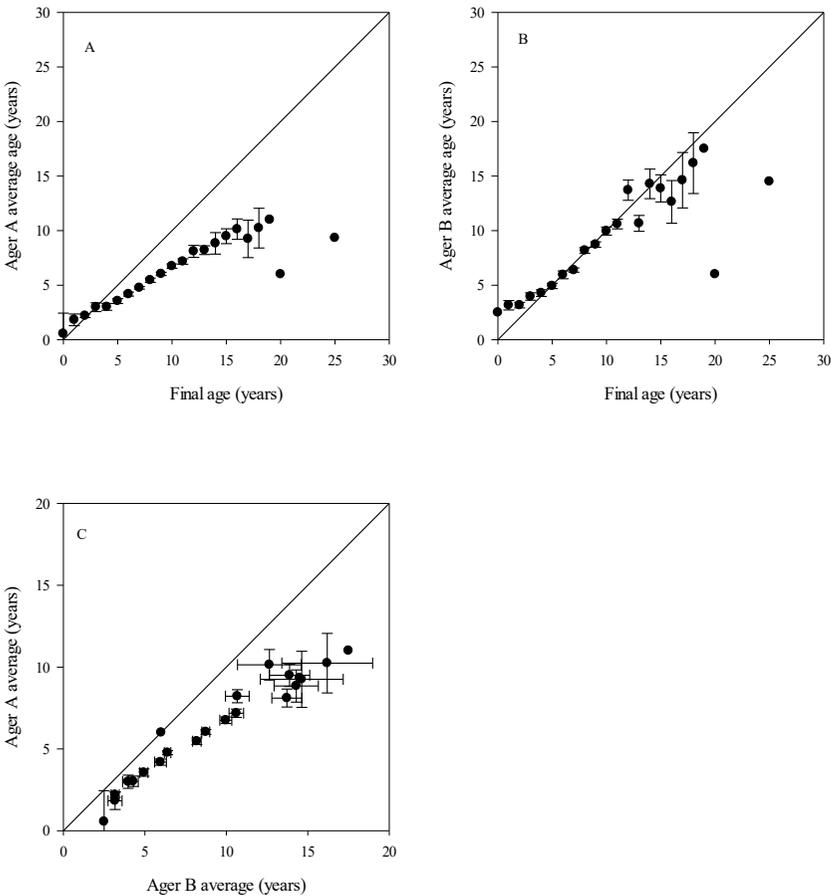
Sex	<i>n</i>	<i>a</i> (intercept)	<i>b</i> (slope)	SE of <i>b</i>	<i>r</i> <sup>2</sup>
Male	149	-4.6742	2.9219	0.3240	0.7833
Female	232	-5.1121	3.0951	0.0558	0.9305
All	381	-5.0192	3.0579	0.0503	0.9062



**Figure 1.** Total length (mm) and whole weight (g) relationship of barred sand bass, all sexes combined. Dashed line represents fitted power curve. Power function and  $R^2$  value is reported.  $n = 379$ .

### Otolith aging

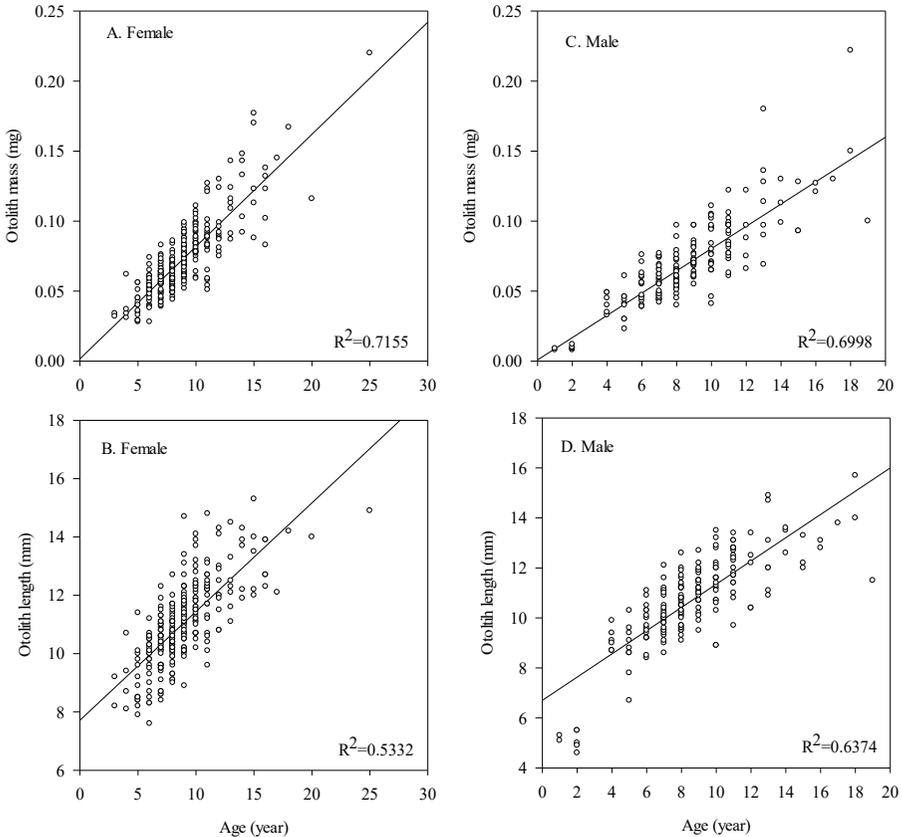
Barred Sand Bass otoliths exhibited the common pattern of alternating translucent and opaque bands radiating out from a central opaque zone (nucleus). The bands started wide then became thinner as they radiated towards the edge until they were no more than a thin line. From the thin otolith wafers, the maximum age given to a female, also the oldest aged fish in the sample, was 25 years old (600 mm TL), and the oldest male was aged at 19 years (453 mm TL). The coefficient of variation (CV) was calculated as 9.9%. Bias plots showed that both agers tended to age younger fish older than the final agreed upon age, and older fish younger than the final agreed upon age. (Figure 2, A and B). Bias plots also showed that agers differed from each other, on average, and generally underaged otoliths (Figure 2, C).



**Figure 2.** Age bias plots of average (n=4) age assigned by readers A and B for Barred Sand Bass, plots A and B. Comparison is between each reader's age and average age against the final agreed upon age. Letters indicate different agers, A and B. Numbers indicate different readings, 1 and 2. Number of otoliths read (n): A1 = 756, A2 = 751, B1 = 740, and B2 = 741. Error bars are 95% confidence intervals.

## Otolith morphometrics

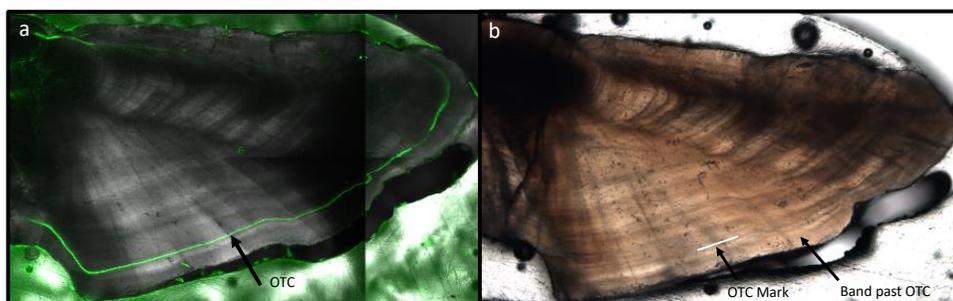
Otolith length and mass increased curvilinearly with age reaching an asymptote. There was a significant difference between sexes for mass and length measurements (ANCOVA;  $p < 0.05$  for both measures), so sexes were analyzed separately. Linear regression models showed that otolith mass explained 72% female and 70% male variation; otolith length explained 53% female and 64% male variation of Barred Sand Bass ages (Figure 3).



**Figure 3.** Linear relationships between otolith morphology and age estimates of *Paralabrax nebulifer*, within the Southern California Bight. The coefficient of determination ( $r^2$ ) values are reported for the relationship between both length and mass with age.  $n = 581$ , for both length and mass measurements. Panels A and B are Females, panels C and D are Males. Solid lines are regression lines.

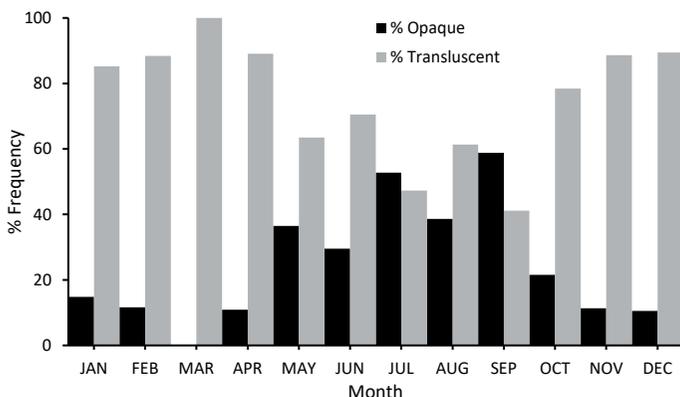
## Validation of annual periodicity and edge analysis

The OTC mark was observed as a fluorescing line on both sagittal otoliths of injected Barred Sand Bass (TL = 426, aged as a 10-year-old fish). One of each translucent and opaque band followed the fluorescing mark and were of the same width as bands before the OTC mark indicating an annual banding pattern (Figure 4).



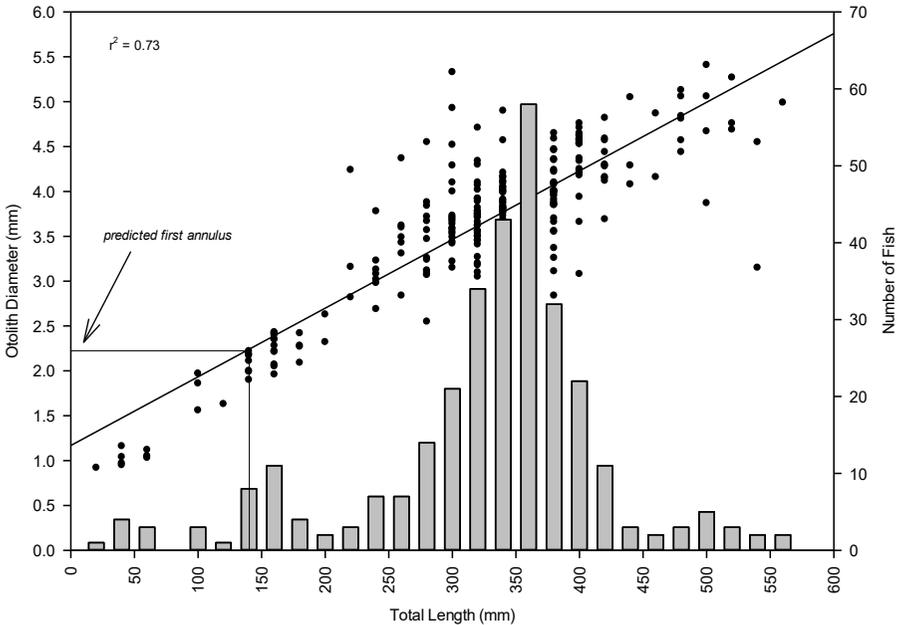
**Figure 4.** Oxytetracycline treated barred sand bass (TL = 426, aged as a 10-year-old fish) thin-sectioned sagittal otolith. a. under fluorescent lighting and b. without. Oxytetracycline mark is indicated by white line and black arrow; the year of growth is also marked. Scale bar is equal to 1 mm.

Opaque bands were found most frequently in the summer months (June to September) and translucent bands were more prevalent during the other months (January to May and October to December). The proportion of opaque and translucent bands during the summer months was approximately 50% for each and during the other months, edges were > 70% translucent (Figure 5) suggesting a seasonal growth pattern.



**Figure 5.** Percent frequency of otolith margin zone (opaque versus translucent) for all aged barred sand bass otoliths captured from 2011 to 2015.

Validation of the first annulus was confirmed by establishing a relationship between otolith diameters of zero and fish total length of zero and one-year aged fish. None of the fish in our sample (n = 10) were the exact total length, so fish were binned in 20 mm increments and the most common mode was the 140 mm bin. Based on a total length of 140 mm for age one fish, the annulus diameter of age one fish was estimated as 2.2 mm. This value corresponded with the predicted annulus diameter of age one fish when otoliths of fish of all ages were included in the regression. Regression analysis showed fish total length explained 73% of otolith diameter (Figure 6).



**Figure 6.** Validation of the annulus on first-year barred sand bass otoliths. Scatter plot of otolith diameter (mm) and fish total length (mm) including distribution of fish at size (total length, mm). Solid line is a regression of otolith diameter and fish total length. Inserted into the graph is the mode of one-year old fish.  $n = 309$ .

### Growth curve determination

We found that the VBGM was the best fit to the size-at-age curve for the male, female and sexes combined (includes unsexed fish) data sets (Table 2). The power function was the next best fit for females and sexes combined; however, it was the poorest fit for males.

Significant differences were found between male and female von Bertalanffy growth model parameters  $L_{inf}$  (ANOVA:  $F = 5.6326$ ,  $P = 0.01792$ ). Therefore, von Bertalanffy growth curves were fit separately for male and female Barred Sand Bass. Both sexes grew relatively fast in early years but slowed down around age five (Figure 7).

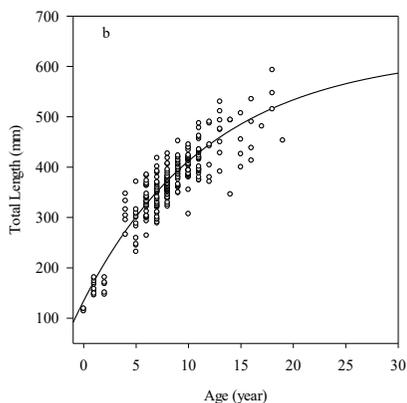
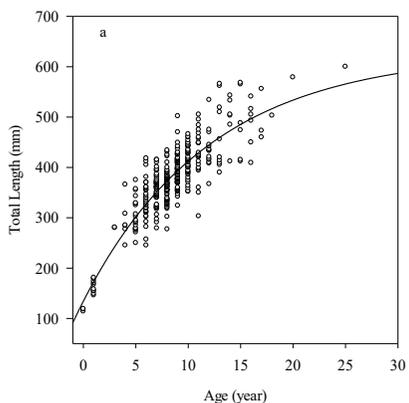
Growth parameters for the current study of all sampled fish ( $n=736$ ) were estimated to be  $L_{inf} = 606$ ,  $k = 0.09$ , and  $t_0 = -2.32$ .

## DISCUSSION

We found and verified that sectioned sagittal otoliths were useful and reliable for estimating age of Barred Sand Bass in southern California. This finding is in line with the previous study from Love et al. (1996) that also found sagittal otoliths of Barred Sand Bass to be appropriate for estimating age. The CV calculated for this species also indicates the viability of using sagittal otoliths for aging of Barred Sand Bass. Campana (2001) suggests that designated CV target levels may be difficult to attain because of morphological and environmental species differences and the complex nature of otoliths. They found that across 117 studies, the median CV was 7.6% and the mode was 5%. Barred Sand Bass are

**Table 2.** Results for model selection. Models ranked by lowest difference in AIC scores ( $\Delta AIC$ ) and larger weight ( $W_i$ ). A lower model AIC and  $\Delta AIC$  indicates a better fit model to the data.

		AIC	$\Delta AIC$	$W_i$
Both Sexes	VBGM	7322.97	0	0.98
	Power	7330.37	7.4	0.02
	Gompertz	7338.5	15.53	0
	Logistic	7357.12	34.15	0
Female	VBGM	3911.64	0	0.91
	Power	3916.4	4.76	0.08
	Gompertz	3920.99	9.35	0.01
	Logistic	3932.42	20.78	0
Male	VBGM	2614.23	0	0.85
	Gompertz	2617.68	3.45	0.15
	Logistic	2625.97	11.74	0
	Power	2723.17	108.94	0



**Figure 7.** Length at age data (open circles) of fit with the von Bertalanffy growth curve (solid black line) of female (a) and male (b) barred sand bass collected within the Southern California Bight, and  $n = 391$ , female and  $n = 266$ , male.

relatively long-lived fish and the otolith-banding pattern was more complex than other species with shorter life spans. Therefore, our reported CV was deemed acceptable and within the range of other long-lived species.

There was a slight sex skew towards more females than males, also a finding from the past study, although the implications of this for Barred Sand Bass populations is not well known. It has been noted that a small number of Barred Sand Bass may be hermaphroditic, which may explain the sex skew (Baca-Hovey et al. 2002). We found the length-weight relationship to be strong, with length a good predictor of weight for males and females combined. Male and female length-weight relationships did not differ significantly from each other,

Otolith banding was also validated with OTC marking of captive adult fish. Often, OTC marking of captive fish is not a reliable method (Campana 2001), because of the inability to control environmental factors. In the case of our captive fish, they were kept in temperature controlled outdoor aquaria that resembled their natural seasonal environment. The creation of both bands during the captive year was of similar width to those prior to OTC marking giving evidence that being in captivity did not inhibit the growth of our OTC marked fish. The location of the first annulus was also confirmed in this study. Establishing the first annulus is an often neglected but important step in aging studies. Studies have found that previous age estimates were inaccurate based on newer studies' location of the first-year annulus (Beamish and McFarlane 1995; Natanson et al. 2006). Edge analysis of Barred Sand Bass otoliths indicated seasonal band formation and reinforces annual periodicity of banding in Barred Sand Bass otoliths. The banding pattern of Barred Sand Bass otoliths showed some seasonality trends. The observed edge pattern consisted of translucent bands appearing more frequently during winter months compared to opaque bands, which were observed in the summer months. The mechanisms of band formation are not well understood but it is widely accepted that they are influenced by temperature and nutrient availability (Weidman and Miller 2000). The winter months produce slow growth with narrow translucent banding (Campana 1999). The summer months of fast growth produce wide opaque bands (Campana 1999).

Very few species of fish are re-evaluated over time for age and growth. Most often, once an analysis occurs and growth parameters have been calculated the data are used for many years to follow, and for some species, this may be appropriate. Commonly, the data are used in stock assessments and other studies that describe a stock to determine the best management strategy. The fit of fish growth to an appropriate growth model is dependent on life history, environment and unseen properties. The shape of the curve may vary, again depending on variations in fish species. The best-fit model for age and growth of Barred Sand Bass was determined to be the von Bertalanffy Growth Model (VBGM). The VBGM is the most used growth model for most marine fish and was used in the past study for Barred Sand Bass (Love et al. 1996). However, unlike the past study, our sample size was large enough to allow accurate fitting of the Von Bertalanffy curve separately for males and females and showed that females grew faster than males, and that females were larger.

The utility of using morphometrics was also explored in this study and we found otolith length and mass may be good indicators of Barred Sand Bass age. Otolith mass was the better predictor of age explaining about 76% of the variation within ages. Considering the difficulty of aging fish species (otoliths of older/larger were difficult to differentiate the annulus versus checks), it seems some otolith morphometrics may be a better alternative to aging of fish otoliths.

Despite a similar maximum age of 25 years in the current study versus 24 years in Love et al (1996), current study had a much smaller  $L_{inf}$  (606 mm) compared to the 1990's study  $L_{inf}$  (662 mm), indicating that maximum size of Barred Sand Bass has decreased over time. However, the growth coefficient  $k$  (0.08 for 1990's and 0.09 for current study) is similar for both studies indicating that growth rate is approximately the same from both studies. Differences in  $L_{inf}$  may be attributed to environmental factors and/or increased fishing pressure. Within the Firth of Clyde in Scotland five species of marine fish were shown to have differing growth rates based on location (Hunter et al. 2016). The locations studied were experiencing different temperature regime changes over decades, starting in the 1980's and continuing to today, like what Barred Sand Bass has experienced in southern California. Another explaining factor is size selective fishing. Changes in phenotype have long been associated with fishing pressure. For example, Sharpe and Hendry (2008) reviewed several studies of changes in commercial fisheries associated with increased fishing pressure and found evidence that fishing pressure is a major driver that influences life history traits that are heritable within a species. The large growth parameter differences found between the 1990's study and this study highlight the importance of updating life history traits for managed marine species.

### ACKNOWLEDGEMENTS

We thank California Department of Fish and Wildlife staff and Los Angeles Sanitation District for collection of fish samples. Heather Gliniak, Miranda Haggerty for critical review of the manuscript. For their contribution to field sampling Kyle Evans, Amy Hartford, Otis Horning, Heather Gliniak, Ricky Kloppe, Tom Mason, and Lilhac Medina. This work was supported in part by the Federal Aid in Sportfish Restoration Act (Grant # F17AF00268). We also thank Ken Oda for Figure 4 images. Finally, to Kelly Voss for her extensive work preparing otoliths and contribution to initial aging protocol.

### Author Contributions

Conceived and designed the study: ETJ-M, CFV, KMP, KMW

Collected the data: ETJ-M, KMP, KMW

Performed the analysis of the data: KMW

Authored the manuscript: KMW

Provided critical revision of the manuscript: ETJ-M, KMP, CFV

### LITERATURE CITED

- Allen, L. G., Hovey, T. E. 2001. Barred Sand Bass. Pages 224–225 in W. S. Leet, C. M. Dewees, R. Klingbeil, and E. J. Larson, editors. California's Living Marine Resources: A Status Report. California Department of Fish and Game, University of California Agricultural Natural Resource Publication SG01-11.
- Beamish, R. J., and D. A. Fournier. 1981. A method for comparing the precision of a set of age determinations. Canadian Journal of Fisheries and Aquatic Sciences 38(8):982–983.
- Beamish, R. J., and G. A. Mc Farlane. The forgotten requirement for age validation in

- fisheries biology. *Transactions of the American Fisheries Society* 112:735–743.
- Beamish, R. J., and G. A. McFarlane. 1995. A discussion of the importance of aging errors, and an application to walleye Pollock: world's largest fishery. Pages 545–566 in D. H. Secor, J. M. Dean, and S. E. Campana, editors. *Recent Developments in Fish Otolith Research*. University of South Carolina Press, Columbia, SC, USA.
- Campana, S. E. 1999. Chemistry and composition of fish otoliths: pathways, mechanisms and applications. *Marine Ecology Progress Series* 188:263–297.
- Campana, S. E. 2001. Accuracy, precision and quality control in age determination, including a review of the use and abuse of age validation methods. *Journal of Fish Biology* 59:197–242.
- Campana, S. E., and J. D. Neilson. 1985. Microstructure of fish otoliths. *Canadian Journal of Fisheries and Aquatic Sciences* 42:1014–1032.
- Chang, W. Y. B. 1982. A statistical method for evaluating the reproducibility of age determination. *Canadian Journal of Fisheries and Aquatic Sciences* 39:1208–1210.
- Collyer, R. D. 1949. Rockbass. Pages 113–115 in the Staff of the Bureau of Marine Fisheries, editors. *The Commercial Fish Catch of California for the Year 1947 with an Historical Review 1916–1947*. Division of Fish and Game, Fish Bulletin No. 74.
- Dalu, T., B. Clegg, and T. Nhiwatiwa. 2013. Length-weight relationships and condition factors of six fish species caught using gill nets in a tropical African reservoir, Zimbabwe. *Transactions of the Royal Society of South Africa* 68(1):75–79.
- Doering-Arjes, P., M. Cardinale, H. Mosegaard. 2008. Estimating population age structure using otolith morphometrics: a test with known-age Atlantic cod (*Gadus morhua*) individuals. *Canadian Journal of Fisheries and Aquatic Sciences* 65:2342–2350.
- Emre, Y., A. Altin, H. Ayyildiz, B. Dolcu, F. Kucuk, and O. Ozen. 2016. Age and growth of *Capoeta pestai* (Actinopterygii: Cypriniformes: Cyprinidae) in a small river entering Lake Egirdir, Turkey. *Acta Ichthyologica ET Piscatoria* 46(2):57–63.
- Enberg, K., C. Jorgensen, E. S. Dunlop, O. Varpe, D. S. Boukal, L. Baulier, S. Eliassen, and M. Heino. 2010. Fishing-induced evolution of growth: concepts, mechanisms and the empirical evidence. *Marine Ecology* 33:1–25.
- Erisman, B. E., L. G. Allen, J. T. Claisse, E. F. Miller, J. H. Murray, and D. J. Pondella, II. 2011. The illusion of plenty: hyperstability masks collapse in two recreational fisheries that target fish spawning aggregations. *Canadian Journal of Fisheries and Aquatic Sciences* 68:1705–1716.
- Eschmeyer, W. N., and E. S. Herald. 1983. *A Field Guide to Pacific Coast Fishes of North America*. Houghton Mifflin Company, Boston, MA, USA.
- Fey, D. P., and T. B. Linkowski. 2006. Predicting juvenile Baltic cod (*Gadus morhua*) age from body and otolith size measurements. *ICES Journal of Marine Science* 63:1045–1052.
- Hunter, A., D. C. Speirs, and M. R. Heath. 2016. Investigating trends in the growth of five demersal fish species from the Firth of Clyde and the Wider Western Shelf of Scotland. *Fisheries Research* 177:71–81.
- Jarvis, E. T., C. Linardich, and C. F. Valle. 2010. Spawning-related movements of *Paralabrax nebulifer*, Barred Sand Bass, in southern California: interpretations from two decades of historical tag recapture data. *Bulletin Southern California Academy of Sciences* 109(3):123–143.
- Jarvis, E. T., K. A. Loke-Smith, K. Evans, R. E. Kloppe, K. A. Young, and C. F. Valle.

2014. Reproductive potential and spawning periodicity in Barred Sand Bass (*Paralabrax nebulifer*) from the San Pedro Shelf, southern California. *California Fish and Game* 100:289–309.
- Katsanevakis, S., and C. D. Maravelias. 2008. Modelling fish growth: multi-model inference as a better alternative to a priori using von Bertalanffy equation. *Fish and Fisheries* 9(2):178–187.
- Lepak, J. M., C. N. Cathcart, and M. B. Hooten. 2012. Otolith mass as a predictor of age in kokanee salmon (*Oncorhynchus nerka*) from four Colorado reservoirs. *Canadian Journal of Fisheries and Aquatic Sciences* 69(10):1569–1575.
- Leung, E., and L. G. Allen. 2016. Year-class strength predicts commercial catch 11 years later for white seabass, *Atractoscion nobilis*, off southern California. *California Fish and Game* 102:175–182.
- Love, M. S., A. Brooks, D. Busatto, J. Stephens, and P. A. Gregory. 1996. Aspects of the life histories of the kelp bass, *Paralabrax clathratus*, and Barred Sand Bass, *Paralabrax nebulifer*, from the southern California Bight. *Fisheries Bulletin* 94:472–481.
- McBride, R. S., A. K. Richardson, and K. L. Maki. 2008. Age, growth and mortality of wahoo, *Acanthocybium solandri*, from the Atlantic coast of Florida and Bahamas. *Marine and Freshwater Research* 59:799–807.
- Matic-Skoko, S., J. Ferri, V. Bartulovic, K. Glavic, and B. Glamuzina. 2011. Age, growth and validation of otolith morphometrics as predictors of age in the forkbeard, *Phycis phycis* (Gadidae). *Fisheries Research* 112:52–58.
- Miller, D.J., Lea, R.N. 1972. Guide to the coastal marine fishes of California. California Department of Fish and Game, Fish Bulletin 157.
- Miller, E. F., D. S. Beck, and W. Dossett. 2008. Length-weight relationships of select common nearshore coastal southern California marine fish. *Bulletin Southern California Academy of Sciences* 107:183–186.
- Natanson, L. J., N. E. Kohler, D. Ardizzzone, G. M. Cailliet, S. P. Wintner, and H. F. Mollet. 2006. Validated age and growth estimates for the Shortfin Mako, *Isurus oxyrinchus*, in the North Atlantic Ocean. *Environmental Biology of Fishes* 77(3):367–383.
- National Marine Fisheries Service (NMFS). 2017. Fisheries economics of the United States, 2015. U.S. Department of Commerce, NOAA Technical Report.
- Ogle, D. H. 2016. *Introductory Fisheries Analyses with R*. CRC Press, Boca Raton, FL, USA.
- Ong, J. J. L., A. N. Rountrey, J. J. Meeuwig, J. Z. Newman, and M. G. Meekan. 2015. Contrasting environmental drivers of adult and juvenile growth in a marine fish: implications for the effects of climate change. *Scientific Reports* 5:10859.
- R Core Team 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available from: <https://www.R-project.org/>
- Schneider, C. A., W. S. Rasband, and K. W. Eliceiri. 2012. NIH Image to ImageJ: 25 years of image analysis. *Nature Methods* 9(7):671–675.
- Sharpe, D. M. T., and A. P. Hendry. 2009. Life history change in commercially exploited fish stocks: an analysis of trends across studies. *Evolutionary Applications* 1752-4571:260–275.

- Treble, M. A., S. E. Campana, R. J. Wastle, C. M. Jones, and J. Boje. 2008. Growth analysis and age validation of a deepwater Arctic fish, the Greenland halibut (*Reinhardtius hippoglossoides*). *Canadian Journal of Fisheries and Aquatic Sciences* 65:1047–1059.
- Weidman, C. R., and R. Milner. 2000. High-resolution stable isotope records from North Atlantic Cod. *Fisheries Research* 46:327–342.
- Williams, J. P., L. G. Allen, M. A. Steele, and D. J. Pondella. 2007. El Niño periods increase growth of juvenile white seabass (*Atractoscion nobilis*) in the Southern California Bight. *Marine Biology* 125:193–200.
- Williams, J. P., J. T. Claisse, D. J. Pondella, L. Medeiros, C. F. Valle, and M. A. Shane. 2012. Patterns of life history habitat use of an important recreational fishery species, Spotfin Croaker, and their potential fishery implications. *Marine and Coastal Fisheries* 4:71–84.
- Zischke, M. T., S. P. Griffiths, I. R. Tibbetts, and R. J. G. Lester. 2013. Stock identification of wahoo (*Acanthocybium solandri*) in the Pacific and Indian Oceans using morphometrics and parasites. *ICES Journal of Marine Science* 70:164–172.

*Submitted 28 February 2020*

*Accepted 10 June 2020*

*Associate Editor was C. Ingel*

FULL RESEARCH ARTICLE

## **Time series modeling and forecasting of a highly regulated riverine system: implications for fisheries management**

ROBERT M. SULLIVAN<sup>1\*</sup> AND JOHN P. HILEMAN<sup>2</sup>

<sup>1</sup> *California Department of Fish and Wildlife, Region 1, Wildlife/Lands Program, P.O. Box 1185 Weaverville, California 96093*

<sup>2</sup> *California Department of Fish and Wildlife, Region 1, Fisheries Program, Trinity River Project, P.O. Box 1185, Weaverville, California 96093*

*\*Corresponding Author: robert.sullivan@wildlife.ca.gov*

Here we apply seasonal time series modeling to flow and fisheries management in a highly regulated river system. Time series modeling is commonly employed to forecast future values of streamflow and extrinsic climate-related seasonal data based on historical information. This method has not been employed in evaluating fish-flow management in highly regulated rivers that experience regular and long-term hydrological fluctuations. Forecasting annual outflow volume and predicting and evaluating its effect on variability in the thermal regime of major river systems, is vital for addressing potential impacts to anadromous and non-anadromous fisheries. Autoregressive Integrated Moving Average (SARIMA) time series analysis was used to predict and describe seasonal variation in flow volume and water temperature for the upper Trinity River in northern California. The objectives were: 1) use a multivariate approach to SARIMA modeling to describe and evaluate seasonal patterns in environmental variables associated with the historical annual time series record in response to implementation of anthropogenic flow-type hydrographs; and 2) relate results to fisheries resources in the upper Trinity River through management recommendations. Raw data representing the historical time series for volume of flow and water temperature variables were partitioned into three time series subgroups. Each subgroup represented a specific flow-type following previous research into the effects of highly managed hydrographs in the upper Trinity River. Subgroups were evaluated based on their efficiency to model and provide accurate operational forecasts of monthly environmental data. Results showed that subcomponents of the historical post-dam time series specific to managed flow-type hydrographs keyed to geomorphologic restoration actions significantly misrepresented the: 1) time series characteristics, 2) seasonal-trend decomposition patterns, and 3) forecast accuracy compared to the baseline pre-restoration time series model. These results effectively nullify use of

managed hydrographs in predicting future forecasts for flow-fish planning and management purposes. Use of time series modeling without reference to continuous intrinsic periods within the historical time series data where flow is anthropogenically manipulated will be misleading when attempting to evaluate the overall characteristics and subsequent future forecasting that derive from such models. By placing environmentally-driven historical time series models into perspective relative to anthropogenically manipulated flow management the needs of both current and future water and fisheries resources will be better optimized notwithstanding the inevitable long-term effects of climate change.

**Key words:** fisheries resources, flow-mediated water temperature, regulated river, river restoration, SARIMA, time series modeling

---

Historically, time series analysis has been employed in building models to detect seasonal trends and forecast future values of water temperature, precipitation, air temperature, evapotranspiration, streamflow, and other climate-based data using regionally-specific historical information (Salas 1993; Adeloje and Montaseri 2002; Papalaskaris and Kampas 2017). Application of time series modeling is expanding with growing concerns about climate change and global warming. This approach requires accurate explanation of the underlying dynamics of river flow. Yet obtaining this kind of information may not always be possible by methods of statistical forecasting using conventional linear regression focused primarily on average values of data (first-order moment) but not variance in data (second-order moment; Casella and Berger 2002; Martínez-Acosta 2020; Attar et al. 2020). Use of time series modeling has not been employed in evaluating issues related to fish-flow management in riverine systems. This observation is particularly true for rivers experiencing regular and long-term hydrological fluctuations keyed to dam operational releases for in-river geomorphological restoration actions, which is the primary focus of this paper.

Variability, uncertainty, and unpredictability are hallmarks of river systems and, by extension, of any in-river restoration initiative (Wissmar and Bisson 2003). Restoration projects on large river systems in the Pacific Northwest carry substantial ecological and economic risk, which highlights the need for improved restoration science (Woelfle-Erskin et al. 2012). Adding to the uncertainty and unpredictability of riverine restoration efforts is the tendency to implement prescriptions at a local-level without consideration of the linkages at nested temporal and spatial scales (Holčík 1996). This practice minimizes insight into modeling longer-term effects that contribute to variability and unpredictability in flow-related restoration efforts and their impacts to fisheries resources (Woelfle-Erskin et al. 2012). For example, restoration flows have traditionally focused on discharge impacts over short time intervals (< 1 year). This strategy is driven primarily by annual needs for in-river geomorphic work without reference to “baseline” or “unimpaired” flow models (Shibatani 2020) synchronized with historical and current tributary flow events that automatically factor in annual variability in climate change. Shortfalls in the outcomes of river restoration have prompted calls to identify and restore processes that support and sustain biological communities, rather than focusing only on river geomorphology (Palmer and Ruhi (2019).

Stochastic Moving Average (ARMA) time series models are based on probability theory that represent the temporal uncertainty of data without a seasonal element (Martínez-Acosta et al. 2020). Modification of ARMA analyses for evaluating stochastic seasonal time

series phenomenon involves Seasonal Autoregressive Integrated Moving Average (SARIMA) models. This technique in combination with the Box-Jenkins (Box and Jenkins 1976) approach, which evaluates autocorrelations among variables as well as lag-lead relationships between variables, has direct application to modeling seasonality and correlation structure in hydrological data associated with forecasting reservoir inflow, outflow discharge, and river water characteristics affecting flow-fish thermal regimes (Stergiou 1991; Pajuelo and Lorenzo 1995; Bari et al. 2015; Papalaskaris et al. 2016). Anthropogenically-induced variable hydrology and its impact on thermal regimes of major riverine systems is a critical factor affecting the physiology, ecology, and life history strategies of resident salmonids and other aquatic organisms (Olden and Naiman 2010; Hallock et al. 1970; McCullough 1999; Carter et al. 2006). Long-term patterns of flow variability have historically selected for organismal life histories related to growth, reproduction, dispersal, and the ability to persist under physical and chemical stress (Palmer and Ruhi 2019). Use of time series modeling is particularly relevant to management of fisheries resources given that most fish are ectothermic, and their life history strategies are directly and functionally affected by variable thermal regimes within their regional and local migratory landscapes (Hildebrand and Goslow 2001). When managing fisheries resources, forecasting outflow volume, and predicting its effect on variability of water temperature is particularly relevant in planning flow releases and understanding the hydrographic characteristics underlying potential impacts to anadromous fisheries resources.

Flow dynamism also is central to a functioning river system and its ability to provide ecosystem services, yet flow alteration is rarely inconsequential (Palmer and Ruhi 2019). Variability in riverine thermal regimes as a function of anthropogenic flow scheduling has the potential to adversely affect run-timing, local migratory behavior, spawning, and early development of juvenile anadromous species, including Coho Salmon (*Oncorhynchus kisutch*), spring- and fall-run Chinook Salmon, and steelhead (*Oncorhynchus mykiss*), together with resident non-anadromous Brown Trout (*Salmo trutta*) and Klamath Smallscale Suckers (*Catostomus rimiculus*; Sullivan and Hileman 2018, 2019, 2020). In northern California, populations of spring-run and fall-run Chinook Salmon (*Oncorhynchus tshawytscha*) in the Klamath Basin have declined significantly in the last 100 years as a function of several linked factors, including a series of dams on the mainstem Klamath and Trinity rivers (Romberger and Gwozdz 2018). All stocks of salmonids in the upper Trinity River are at their lowest levels since 2007. The upper Trinity River has experienced repeated fluctuations in the seasonal volume of flow and thermal regime as a function of water management policy, in-river anthropogenic actions centered around geomorphological restoration activity, and attempts to control disease using artificially augmented pulsed flows since 2003 (Sullivan and Hileman 2018). These activities directly affect migration and run-timing in both non-anadromous and anadromous salmonids linked to the expression of regionally adapted life history strategies (Sullivan and Hileman 2020).

The objectives of this research were threefold. First, a multivariate approach to SARIMA time series modeling was used to describe seasonal patterns in environmental variables potentially influenced by implementation of specific anthropogenic flow-type hydrographs. Second, we tested the hypothesis that subcomponents of the historical time series data representing specific in-river restoration actions significantly misrepresent the time series characteristics and forecast accuracy of seasonal flow volume and water temperature compared to a “baseline” pre-restoration time series model. Third, we relate results of our research to management of fisheries resources in the upper Trinity River through recommen-

dations focused exclusively on time series modeling and analysis. Forecasting plays a critical role in fisheries management because it precedes planning which, in turn, precedes decision making (Makridakis et al. 1983; Stergiou et al. 1997). By placing environmentally-driven historical time series models into perspective relative to anthropogenically manipulated flow management, the needs of both current and future water and fisheries resources will be better optimized and managed notwithstanding the inevitable long-term effects of climate change.

## METHODS

### Study area

The Trinity River is in northwestern California and is the largest tributary of the Klamath River system (Figure 1A). Construction of Trinity and Lewiston dams occurred in the early 1960s. Trinity Dam creates Trinity Reservoir, storing up to 3,022 m<sup>3</sup> of water. Lewiston Reservoir, formed by Lewiston Dam, is located 11.8 km downstream of Trinity Dam, which serves as a re-regulating reservoir for flow to the Trinity River and diversion to the Sacramento River Basin, comprising the Trinity River Division of the Central Valley Project (Sullivan and Hileman 2019). The Trinity River system is not connected geologically to the Sacramento River system of the Central Valley. From Lewiston Dam, the Trinity River flows ~ 180 kilometers before joining the Klamath River at the township of Weitchpec, California. The Klamath River flows for an additional 70 km before entering the Pacific Ocean. Trinity River Hatchery is located immediately below Lewiston Dam. From a management perspective, the upper 63.1 rkm of the Trinity River or “mainstem,” ends at the confluence of the North Fork Trinity River and the Trinity River proper. This section of the river is the primary focus of in-river restoration activities by the Trinity River Restoration Program (TRRP 2020). The focus of our study was the upper-most section of the mainstem just below Lewiston Dam and the Trinity River Hatchery, which is the upper limit to anadromy on mainstem.

### Managed flows and release schedule

The TRRP created by the Record of Decision, henceforth called “ROD” (USBR 2000), mandated a plan for restoration of 63.1 km of the upper Trinity River and its fish and wildlife populations. The Trinity River Mainstem Fishery Restoration Environmental Impact Statement was the basis for the ROD (TRFES 1999). This restoration strategy included: 1) flow management through manipulation of the annual hydrograph, 2) mechanical channel rehabilitation, 3) sediment management, 4) watershed restoration, 5) infrastructure improvements, 6) adaptive environmental assessment and monitoring, and 7) environmental compliance and mitigation. Schedules for annual flow releases for the Trinity River are established based on water year type<sup>1</sup> and restoration needs (Appendix I; TRRP 2020). As of water year 2020 the proportion of water scheduled to be removed from the Lewiston Reservoir and diverted to the Central Valley is 61% of the allotment. The remainder (39%)

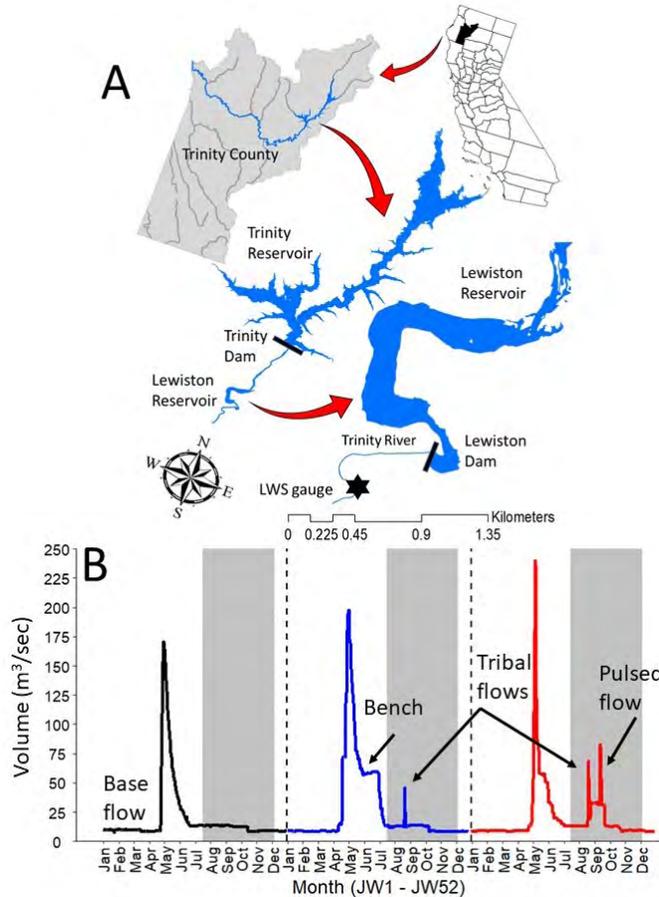
---

<sup>1</sup> The term “water year” defined by the United States Geological Survey is “the 12-month period 1 October (of any given year) through 30 September 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 “1999” water year. [https://water.usgs.gov/nwc/explain\\_data.html](https://water.usgs.gov/nwc/explain_data.html)

is scheduled to be released into the into the Trinity River. Detailed descriptions and summaries of specific flow schedules and restoration actions are provided elsewhere (TRRP 2020; Sullivan and Hileman 2019).

### Data collection and sampling

To test our hypothesis, raw data representing the historical time series data for volume of flow and water temperature were partitioned (fixed portioning; Prasad 2019) into three time series subgroups. Each subgroup corresponded to specific hydrological flow-types following previous research into the effects of highly managed hydrographs on the upper Trinity River and its fisheries resources (Figure 1B<sup>2</sup>; Sullivan and Hileman 2020). These subgroup flow-types included: 1) “baseline” PreROD flows (1995 – 2002), 2) ROD flows (2005 – 2011, 2017), and 3) Pulse flows (2012 – 2016, 2018). ROD and Pulse flow-types represented only those continuously unbroken sequences of years in which specific managed



**Figure 1.** A) Map of Trinity County and location of Trinity Dam, Lewiston Dam, Trinity River Hatchery, and Lewiston Water Quality Gauge (LWS) within the upper reach of traditional spawning grounds 1.7 rkm downstream of hatchery. B) Examples of hydrographs representative of different flow-types used in time series analyses. Managed hydrographs are associated with ROD and Pulse flow-types typically implemented between Julian week 13 and 40. Gray shaded areas correspond to run-time presence of various species of salmonids in the upper river.

2 Hoopa Valley Tribal Boat Dance flows are scheduled in odd years for ceremonial purposes. During this time, the United States Bureau of Reclamation increases the volume of flow from Lewiston Dam into the Trinity River in support of this ceremony in the town of Hoopa, California.

hydrographs were implemented. Daily recordings of telemetered digital data were used to assess the seasonal extent of variability in the annual thermal regime that characterizes the upper Trinity River. These data were obtained from the United States Bureau of Reclamation, Lewiston Water Quality Gauge (LWS; DWR 2020) located 1.7 rkm downriver from Lewiston Dam (river-km 178.2; UTM 516,634 m E and 4,507,678 m N; elevation 558 m). Digital data obtained included averaged daily: 1) flow volume (ADFV  $\text{m}^3/\text{s}$ ), 2) minimum air temperature (MIAIR degrees Celsius [ $^{\circ}\text{C}$ ]), 3) maximum air temperature (MXAIR  $^{\circ}\text{C}$ ), 4) minimum water temperature (MIWAT  $^{\circ}\text{C}$ ), maximum water temperature (MXWAT  $^{\circ}\text{C}$ ); and 5) a measure of extreme variability in water temperature (ADWTV [average – minimum] + [maximum – average]  $^{\circ}\text{C}$ ). The LWS gauge was chosen because there are no other sources of inflow from the watershed or major tributaries between the LWS gauge and Lewiston Dam. As a result, this section of the river is not inadvertently influenced by other local watershed conditions. Further, this location was the “standard” used in all National Environmental Protection Act (NEPA) assessments and flow augmentation analyses of fluctuations in river water temperature, specific to the upper Trinity River out of Lewiston Dam since 1997 (Magneson and Chamberlain 2014). Importantly, this gauge provides the best location for measuring water temperature conditions nearest to the hatchery as hatchery-origin Chinook Salmon as well as other natural-origin salmonids traditionally spawn in this segment of the upper-most reach.

## Statistical analyses

*Standard statistics.*—All statistical tests performed used the R-suite of statistical programs (R Core Team 2020) and statistical significance for all analyses was set at  $p < 0.05$ . Prior to implementing statistical analyses, visual assessment of each environmental variable was conducted using two goodness-of-fit plots: 1) theoretical density plots of histograms against fitted density functions; and 2) Q-Q plots of the theoretical quantiles against empirical ones with emphasis on lack-of-fit at the tails of distributions, which were evaluated by use of the Akaike information criterion (AIC; Package “MuMIn;” Appendix II). A follow-on statistical evaluation using the Anderson-Darling (A) test statistic (Stephens 1986) similarly showed that all environmental metrics were not normally distributed (minimum air temperature:  $A = 14.7$ ,  $p < 0.001$ ,  $n = 5,752$ ]; maximum air temperature:  $A = 80.7$ ,  $p < 0.001$ ,  $n = 5,752$ ]; minimum water temperature:  $A = 10.9$ ,  $p < 0.001$ ,  $n = 8,055$ ]; maximum water temperature:  $A = 14.5$ ,  $p < p < 0.001$ ,  $n = 8,055$ ]; extreme variability in water temperature:  $A = 276.1$ ,  $p < 0.001$ ,  $n = 8,042$ ]; flow volume:  $A = 148.5$ ,  $p < 0.001$ ,  $n = 8,401$ ). Thus, all subsequent statistical analyses used non-parametric or semi-parametric<sup>3</sup> statistical methods (McDonald 2014; Tsiatis et al. 2006). Spearman’s rank correlation rho ( $r_s$ ) 2-tailed test was used to calculate the strength and direction of the relationship between two variables, expressed as a monotonic relationship, whether linear or not (Corder and Foreman 2014). Kruskal-Wallis Chi-square ( $\chi^2$ ) rank sum tests evaluated each designated variable accompanied by follow-on planned pairwise comparisons between each designated group using the Dunn test statistic (Z). All p-values were adjusted using the Benjamini-Hochberg method (Benjamini and Hochberg 2000; Machiwal and Madan 2006).

Principal components analysis (PCA; Program “FactoMineR”) was used to describe variation, identify variable selection, discard redundant variables, and assess seasonal varia-

<sup>3</sup> In statistics, a semiparametric model is a statistical model that has parametric and nonparametric components. [https://en.wikipedia.org/wiki/Semiparametric\\_model](https://en.wikipedia.org/wiki/Semiparametric_model)

tion in each environmental variable. Component axes that accounted for > 1% of the total variation in “attribute space” were retained for further analysis among flow-types for each time series. This method is generally preferred for numerical accuracy as resulting principal components are orthogonal, thus minimizing multicollinearity between model predictors, with the goal of identifying a smaller subset of variable components that capture the majority of variance in predictors (Everitt and Hothorn 2011).

*Generalized additive models.*—Semi-parametric generalized additive modeling (GAM; Package “mgcv;” Wood 2017) was used in regression of each environmental variable (Hastie and Tibshirani 1990; Madsen and Thyregod 2011; Wood 2017). Response curves generated from each GAM showed the relationship between the fitted function and the response variable. Smooths were “centered” to ensure model identity and summed to zero over covariate values. Statistics reported by each GAM included: 1) F-statistic (approximate significance of smooth terms), 2) p-values and 95% confidence bands for spline lines (Nychka 1988), 2) adjusted regression coefficients for each model ( $R^2$ .Adj.), 3) estimated residual degrees of freedom (Ref.df.), and 4) proportion of null deviance explained (Dev.Exp.). The Spearman’s rank correlation coefficient was used as a follow-on procedure to assess strength and significance of trends in each variable delineated by smooth terms. Ranked correlation was used because GAMs lack a statistical inference procedure and formal parameter of goodness of the fit, which makes interpretation of output potentially complicated (Package “fitdistrplus;” Diankha and Thiaw 2016). The gamma error-structure (family = “Gamma” [link = “log”]) was used to assess the error distributions in fluctuations of each environmental variable; and the AIC information criterion was used to select the most parsimonious error distribution for each environmental attribute (Package “MuMIn;” Akaike 1973; Burnham and Anderson 1998).

*Seasonal-trend decomposition and adjustment.*—Historical annual data were aggregated by month. Months were used instead of Julian weeks (52 weeks/year) because the historical time series data were not detailed enough for each environmental variable to justify using weekly subdivisions. Use of Julian weeks would have been preferable because they would have imparted greater detail to the analyses. Seasonal-Trend-Loess (STL) decomposition component analysis was used to remove the seasonal effect from each time series variable to facilitate understanding of trends in the dataset. The STL method using local polynomial regression was fitted by a least squares algorithm to partition the time series of each dataset into three components: 1) trend (Tt), 2) seasonality-cycle (St), and 3) remainder (Rt), written as:  $y_t = St + Tt + Rt$ , for  $t = 1$  to  $N$  measured data points (Hydman and Athanasopoulos 2014). Once each component was fit by the STL model, they were subtracted from the raw time series data for each environmental variable to give the remainder component of each model. Thus, the remainder component equates to the residuals derived from the seasonal plus trend fit, or “random” time series (Cleveland et al. 1990; Cleveland et al. 1992). Ability to determine if a single measurement was unusually low or high by looking at the remainder terms is a typical use of seasonal decomposition. Locally weighted regression and scatterplot smoothing (Loess) was used to estimate nonlinear relationships, in which the entire procedure is iterated using a back-fitting algorithm. Inter-quartile range (IQR) calculations for x-values were generated by STL modeling of the trend, seasonality, and remainder components used to gain a relative measure of how spread-out points were in the original time series dataset (Zar 2010). For a normal distribution with standard deviation  $\sigma$ ,  $IQR = 1.35\sigma$ .

*Time series modeling and seasonality.*—Goals of the time series analyses were to: 1) describe the pattern indicated in the time series data, 2) identify the nature of the phenom-

enon represented by the sequence of observations and integrate with seasonally variable environmental effects, and 3) forecast future values in each time series model for each environmental attribute. To accomplish these goals, time series analysis assumes that successive values in the data file represent consecutive measurements taken at equally spaced time intervals (Hill and Lewicki 2007). Thus, years 2003, 2004, and 2018 were not included in the Pulse flow time series model, nor was 2017 included in the ROD flow time series model as illustrated in Figure 1A. Importantly, the years removed were consistent with the consecutive annual monthly patterns exhibited by both managed flow-types. Retention of these years and months would have provided additional detail by contributing to the robustness of statistical tests as a function increasing sample size for each anthropogenic subcomponent of each restoration time series model.

Seasonality is a significant concern when modelling time series weather data unique to a particular region. Because all environmental data evaluated herein exhibited seasonality, SARIMA modeling (Program “astsa,” Shumway and Stoffer 2017) was used to evaluate each univariate time series and to inspect model fit diagnostics (Nau 2017; Hyndman and Athanasopoulos 2018). A SARIMA model was fitted to each environmental variable for each flow-type subcomponent of the historical time series, with the intent to discover the most appropriate match of each time series data point to previous values of the same time series, and to perform future forecasts. Seasonal components of each model were written using uppercase letters, whereas non-seasonal components were referenced in lowercase letters and written in the form: SARIMA (p, d, q) (P, D, Q)m, where p = non-seasonal order (autoregressive model AR[p]), d = non-seasonal differencing, q = non-seasonal order moving average (MA), P = seasonal (AR) order, D = seasonal differencing, Q = seasonal (MA) order, and m = number of periods per season indicating the time interval of repeating seasonal sequences. The seasonal portion of each model was comprised of components resembling the stochastic non-seasonal terms of an ARIMA model but included backshift operators of the seasonal period and multiplied with the non-seasonal elements of the model (Brownlee 2018). SARIMA models allow the user to generate synthetic time series considering cyclical variations in the observed series records (Cox and Miller 1977; Chatfield and Xing 2019). Differencing (d, D) is the difference between a value and a value with lag that is a multiple of m (Hyndman and Athanasopoulos 2018).

*SARIMA, autocorrelation, and forecasting.*—Each SARIMA model was fitted to monthly values of maximum air temperature, extreme variability in water temperature, and flow volume for each flow-type, which takes in arguments in the following order: data, ARIMA inputs (p, d, q), SARIMA inputs (P, D, Q), and seasonal lag S. A primary advantage of SARIMA is that it automatically differences (d = 1, D = 1) each seasonal time series model consistent with the number of differences recommended by use of the `ndiff()` function, along with estimating the lowest AIC values and measures of variance ( $\sigma^2$ ) for each data set as different choices of p and q were considered. This process generally results in the best-fit model for use in follow-on forecasting. The `auto.arima()` function without drift was used to determine the order of each SARIMA model (Package “forecast”) in which the algorithm conducts numerous iterations and checks in a search for all possible models within the order constraints provided (Hyndman and Khandakar 2008). This stepwise algorithm returns the best “fit” model with the lowest AIC value and automatically differences the time series to make it stationary (Hyndman and Khandakar 2008; Wang et al. 2006). Residuals were used to investigate the relationship of each time point to each previous time point in the distribu-

tion of consecutive annual fluctuations in each environmental variable for each time series model. Follow-on assessment was conducted to ascertain if model residuals were random using autocorrelation (ACF) and partial autocorrelation (PACF) plots.

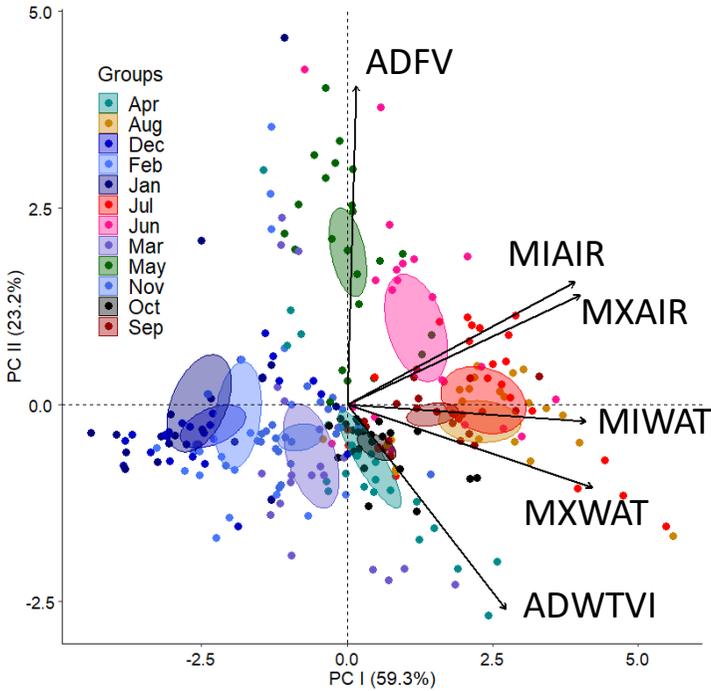
Augmented Dickey-Fuller tests gauged the extent of stationarity in each time series model and Box-Pierce tests ( $\chi^2$ ) determined whether any group of autocorrelations of a time series were different from zero (Box and Jenkins 1970; Fuller 1976; Ljung and Box 1978). Parsimony was used to evaluate performance and to validate each model for each time series using the minimum AIC statistic prior to forecasting. Once the best-fit SARIMA model was identified, the function `sarima.for()` was used to provide a forecast for the next “future” 36-month time intervals for each time series (Package forecast v8.10). Accuracy of forecasting was evaluated by use of the Mean Absolute Percentage Error (MAPE) measure, which assumes that  $MAPE \leq 10\%$  or  $11 - 20\%$  is considered an excellent to good forecasting estimate, respectively (Lewis 1982; Moreno et al. 2013; Hyndman and Athanasopoulos 2018). After estimating the parameters of each ARIMA model for each environmental variable by flow-type, their adequacy was evaluated graphically by visually inspecting their standardized residuals, ACF graphs, Q-Q plots, and p-values for the Ljung-Box test. Due to space limitations and the number of panels that resulted for each variable by flow-type, a graphic illustration was provided only for the PreROD flow-type.

## RESULTS

### Historical annual fluctuations in flow volume and water temperature

Principal components analysis of months using environmental variables merged with plot loadings showed a gradation in the seasonal distribution from cold-wet (winter-fall) to warm-dry (spring-summer) climatic conditions along the axis of PC I for the surrounding riverine corridor downriver from Lewiston Dam (Figure 2; Table 1). A total of 91.2% of the variation among months was explained on the first three PCs. As shown by the loading, relationship, and direction of each arrow, all variables vectored heavy and positive along PC I (59.3%) except flow volume, which vectored positive along PC II (23.2%) particularly during the months of May followed by June. Because of the strong correlation between individual measures of air temperature ( $r_s = 0.890$ ,  $n = 204$ ) and water temperature ( $r_s = 0.920$ ,  $n = 276$ ) only maximum water temperature, extreme variability in water temperature, and flow volume were kept for further analyses to reduce collinearity (Everitt and Hothorn 2011).

From 1994 to 2018, GAM regression identified a significant trend in the smooth term of the annual response curve in maximum air temperature for the upper-most section of the mainstem Trinity River above the Lewiston Water Quality gauge (Table 2). Yet deviance explained was not robust relative to all other environmental variables (Dev.Exp = 0.04%) and the strength of the relationship was extremely weak ( $r_s = 0.038$ ,  $p = 0.004$ ,  $n = 5,752$ ). Significant annual trends in flow volume, maximum water temperature, and extreme variability in water temperature also were not robust. Whereas both measures of water temperature showed positive annual trends, this relationship was negative for flow volume (Figure 3). Additionally, the relationship between annual variation in maximum air temperature was significantly correlated with both water temperature variables but not with flow volume (Table 2; Figure 4). Thus, although the relationship between annual fluctuations in water temperature was significant and positive, both variables were inversely correlated with



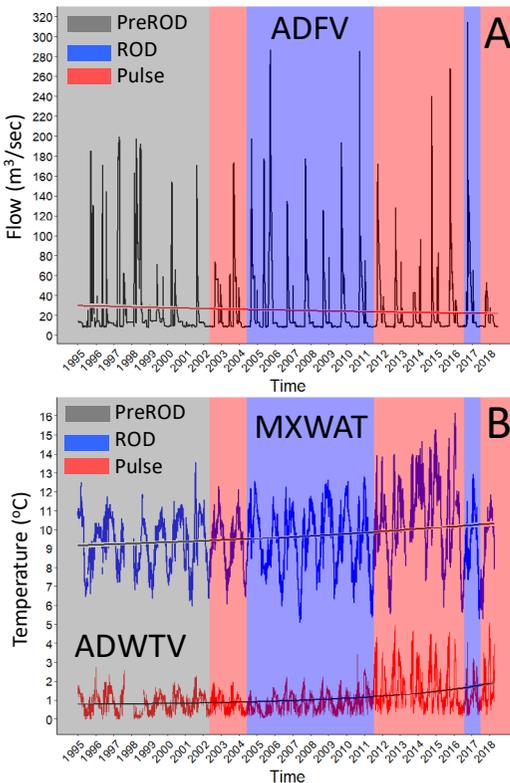
**Figure 2.** Principal components analysis (PCA) of monthly variation in environmental variables plotted along the first two components: MIAIR = minimum air temperature, MXAIR = maximum air temperature, MIWAT = minimum water temperature, MXWAT = maximum water temperature, ADWTV = extreme variability in water temperature, and ADFV = flow volume. All temperatures in degrees Celsius (°C) and volume of flow in m<sup>3</sup>/second.

**Table 1.** Principal components analysis of similarities among months merged with plot loadings. Variables were average daily environmental attributes: MIAIR = minimum air temperature, MXAIR = maximum air temperature, MIWAT = minimum water temperature, MXWAT = maximum water temperature, ADWTV = extreme variability in water temperature, and ADFV = flow volume. All temperatures in degrees Celsius (°C) and volume of flow in m<sup>3</sup>/second.

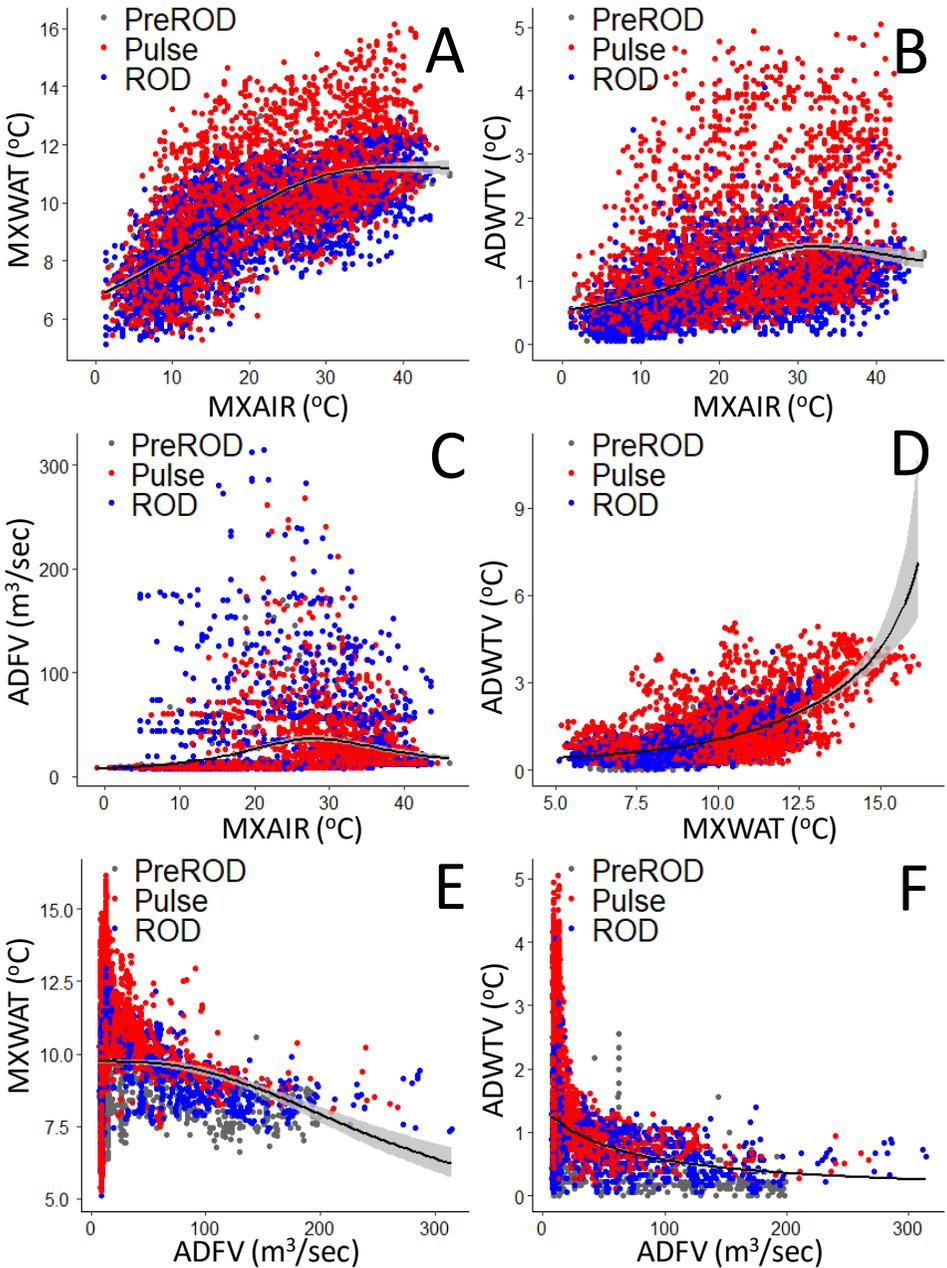
Measure	Dimension		
	PC I	PC II	PC II
Variance	3.6	1.4	0.5
Percent	59.3	23.2	8.7
Cumulative percent	59.3	82.5	91.2
Variable	Percent PC I	variable PC II	contribution PC II
ADWTV	0.03	57.26	29.60
MIAIR	20.95	8.46	2.14
MXAIR	21.84	6.78	0.32
MIWAT	22.92	0.15	10.28
MXWAT	24.14	3.81	0.01
ADWTV	10.12	23.54	57.66

**Table 2.** Summary of generalized additive modeling using GAM regression and the Spearman rank correlation coefficient ( $r_s$ ) statistics for average daily: 1) ADFV = flow volume, 2) MXWAT = maximum water temperature, and 3) ADWTV = extreme variability in water temperature. All temperatures in degrees Celsius ( $^{\circ}\text{C}$ ) and volume of flow in  $\text{m}^3/\text{second}$ .

Variable comparison	GAM regression model					Spearman rank correlation		
	F-statistic	Ref.df.	p-value	R <sup>2</sup> .Adj.	Dev.Exp.	n	$r_s$	p
Relationships between environmental variables versus year								
MXAIR ~ year	12.5	2.0	< 0.001	0.00	0.4%	5,752	0.038	< 0.004
MXWAT ~ year	164.1	2.0	< 0.001	0.04	3.6%	8,055	0.190	< 0.001
ADWTVI ~ year	766.3	2.0	< 0.001	0.13	13.4%	8,042	0.354	< 0.001
ADFV ~ year	19.1	1.8	< 0.001	0.00	0.8%	8,401	-0.061	< 0.001
Relationships among environmental variables								
MXWAT ~ MXAIR	2,265.0	2.0	< 0.001	0.47	47.1%	5,664	0.672	< 0.001
ADWTVI ~ MXAIR	690.4	2.0	< 0.001	0.14	20.2%	5,664	0.369	< 0.001
ADFV ~ MXAIR	231.4	2.0	< 0.001	0.07	16.5%	5,721	0.211	< 0.001
ADWTVI ~ MXWAT	2,052.0	2.0	< 0.001	0.45	34.7%	8,042	0.626	< 0.001
MXWAT ~ ADFV	111.5	2.0	< 0.001	0.03	2.6%	8,012	-0.143	< 0.001
ADWTVI ~ ADFV	770.2	2.0	< 0.001	0.08	12.3%	7,999	-0.273	< 0.001



**Figure 3.** Generalized additive model (GAM) regression plots of annual variation in averaged daily: flow volume (ADFV), maximum water temperature (MXWAT), and extreme variability in water temperature (ADWTV). Shaded smooth areas indicate 95% point-wise standard error for each curve surrounding each fitted GAM function (centered black line).



**Figure 4.** Generalized additive model (GAM) regression plots of annual variation in averaged daily: flow volume (ADFV), maximum water temperature (MXWAT), and extreme variability in water temperature (ADWTV) versus maximum air temperature (MXAIR; A – C), and between environmental variables (D – F) for each flow-type. Shaded smooth areas indicate 95% point-wise standard error for each curve surrounding each fitted GAM function (centered black line).

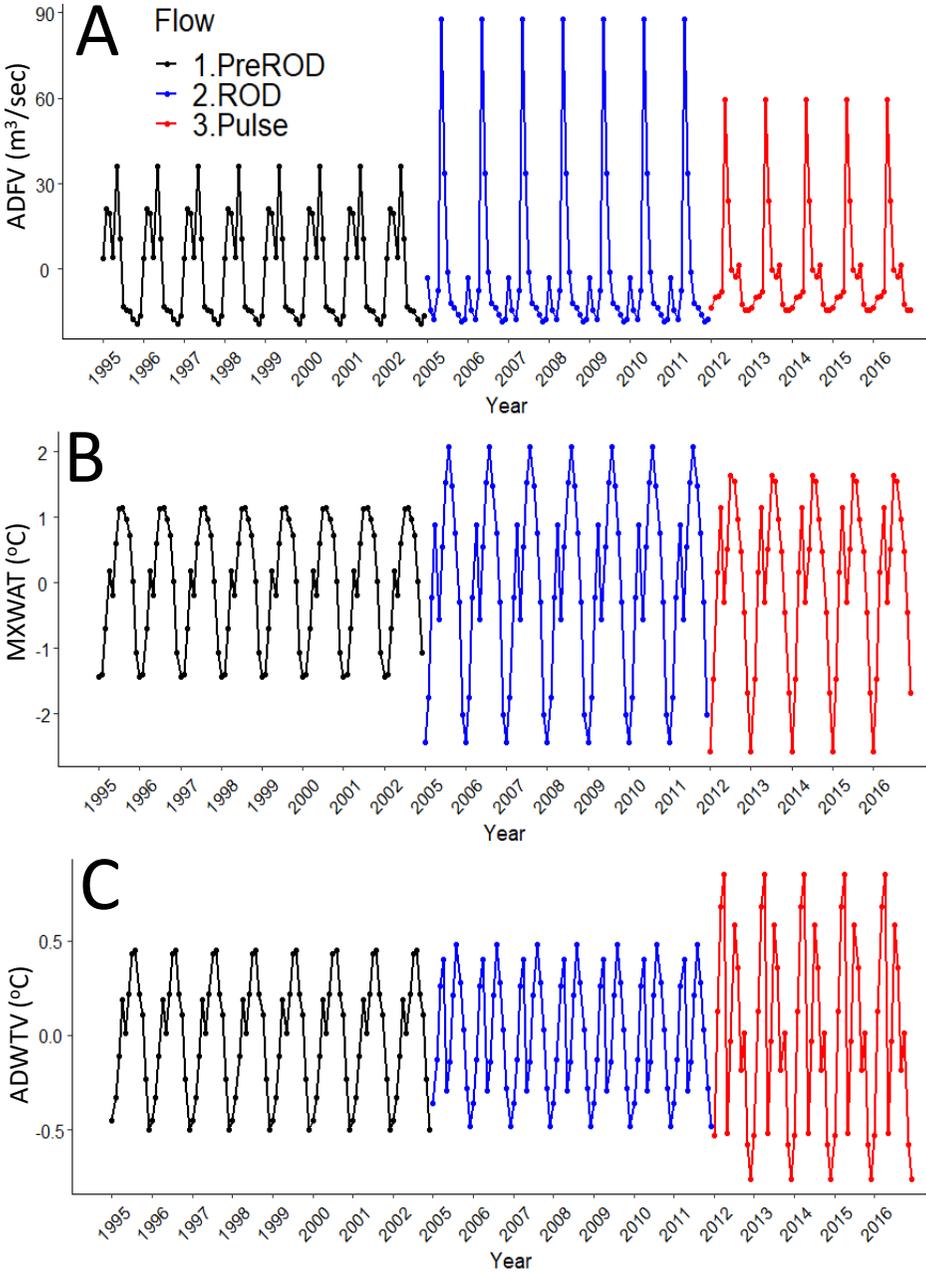
fluctuations in flow volume such that when flow increases water temperature decreases as expected. Importantly, Kruskal-Wallis Chi-square ( $\chi^2$ ) rank sum tests revealed significant overall differences for each flow-type hydrograph for each measure of water temperature and flow volume. Follow-on post-hoc pairwise comparisons also showed significant differences between flow-types for all environmental attributes (Table 3). To recap, not only were there significant annual trends in the raw data for the complete historical time series model for each environmental variable as illustrated by GAM regression, there also were significant overall and post-hoc pairwise annual differences between flow-types for each environmental attribute.

**Table 3.** Comparison of historical time series data based on raw data collected using the Kruskal-Wallis rank sum test ( $\chi^2$ ) for environmental variables by flow-type followed by planned post-hoc Dunn test statistics (Z) of all pairwise comparisons. Variables were average daily: ADFV = flow volume, 2) MXWAT = maximum water temperature, and 3) ADWTVI = extreme variability in water temperature. All temperatures in degrees Celsius (°C) and volume of flow in m<sup>3</sup>/second; p-values were < 0.05 = \*, < 0.01 = \*\*, < 0.001 = \*\*\*.

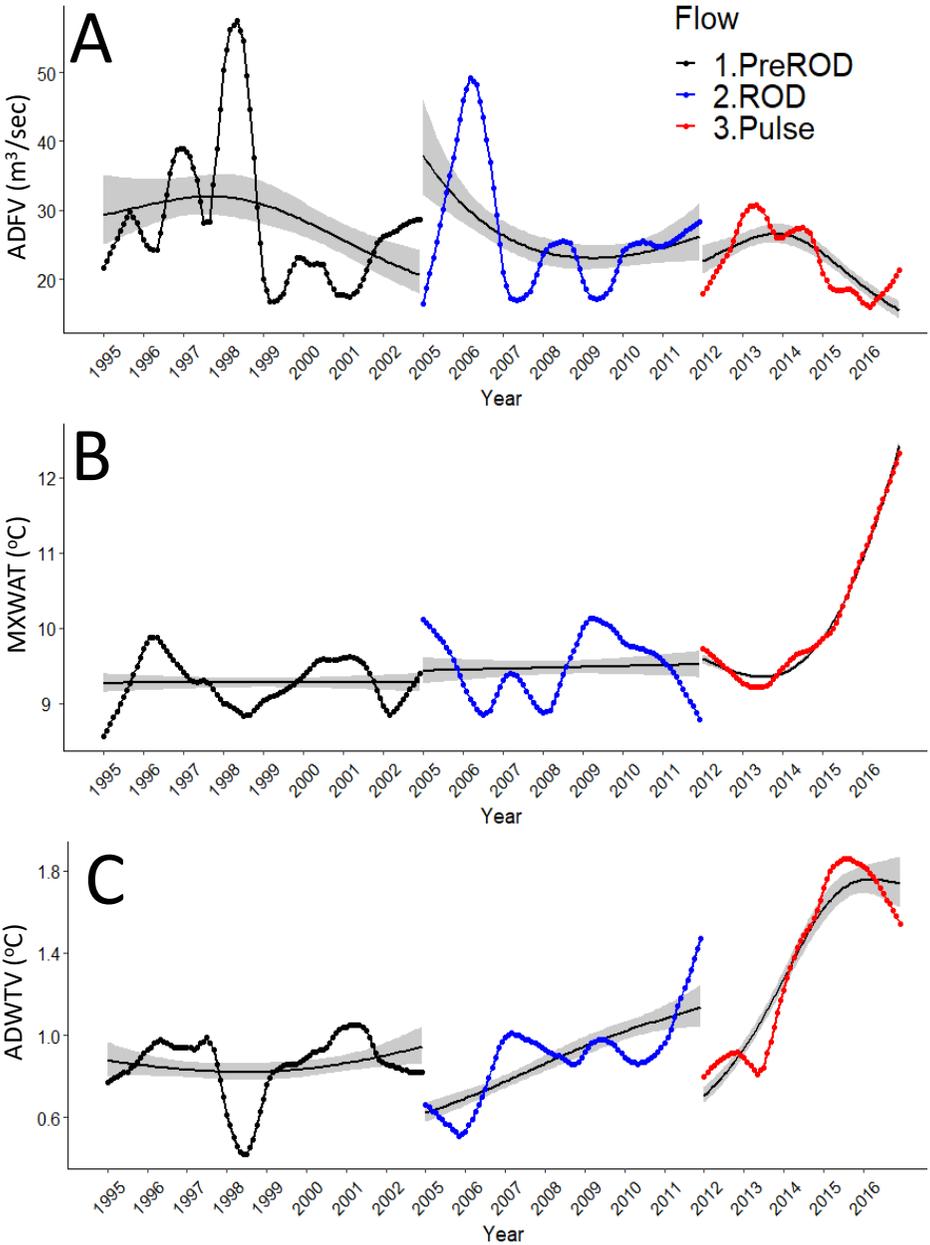
ADFV ( $\chi^2 = 176.2$ , df = 2, p < 0.001***)			
Group(i)	Group(j)	Z	p.adj
PreROD (n = 2,619)	Pulse	9.7	< 0.001***
PreROD	ROD (n = 2,885)	12.8	< 0.001***
Pulse (n = 2,897)	ROD	3.2	< 0.001***
MXWAT ( $\chi^2 = 330.0$ , df = 2, p < 0.001***)			
Group(i)	Group(j)	Z	p.adj
PreROD (n = 2,396)	Pulse	16.9	< 0.001***
PreROD	ROD (n = 2,908)	3.5	< 0.001***
Pulse (n = 2,751)	ROD	14.1	< 0.001***
ADWTVI ( $\chi^2 = 594.9$ , df = 2, p < 0.001***)			
Group(i)	Group(j)	Z	p.adj
PreROD (n = 2,383)	Pulse	21.9	< 0.001***
PreROD	ROD (n = 2,908)	2.7	< 0.006**
Pulse (2,751)	ROD	20.1	< 0.001***

### Seasonal-Trend-Loess (STL) decomposition

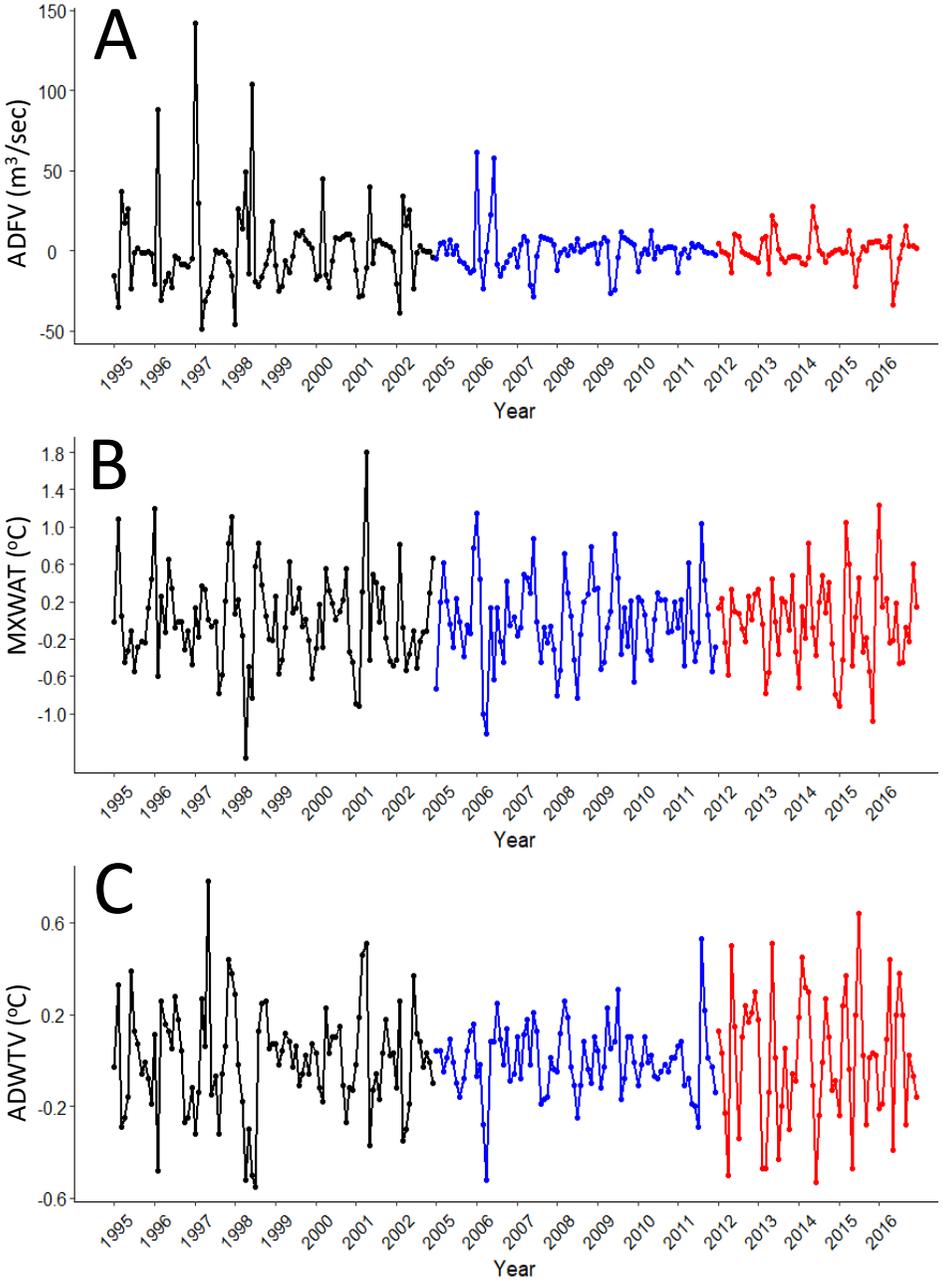
A comparison between the historical raw data (Figure 3) and subdivided monthly time series models using STL decomposition of each environmental variable by flow-type showed loss of detail, resolution, and therefore information content when partitioning on a monthly basis relative to Julian week or daily time series schedules (Figure 5 – Figure 7). Nonetheless, there were obvious qualitative visual differences in the subdivided monthly data among hydrographs. For example, seasonal components produced for each environmental variable revealed distinct visual differences among flow-types for each time series model (Figure 5A – 5C). Each flow-type time series showed a regular pattern of variation in each environmental variable with monthly periodicity. This periodicity indicated that each month had the same repeating pattern that changed every 30 days reflecting long-term



**Figure 5.** Results of the time series decomposition analyses showing plots of the Seasonal-Trend-Loess (STL) seasonal monthly component for each environmental variable; including average daily: flow volume (ADFV), maximum water temperature (MXWAT), and extreme variability in water temperature (ADWTV) by flow-type (PreROD, ROD, Pulse).



**Figure 6.** Results of the time series decomposition analyses showing plots of the Seasonal-Trend-Loess (STL) trend monthly component for each environmental variable; including average daily: flow volume (ADRV), maximum water temperature (MXWAT), and extreme variability in water temperature (ADWTV) by flow-type (PreROD, ROD, Pulse).



**Figure 7.** Results of the time series decomposition analyses showing plots of the Seasonal-Trend-Loess (STL) remainder monthly component for each environmental variable; including average daily: flow volume (ADFV), maximum water temperature (MXWAT), and extreme variability in water temperature (ADWTV) by flow-type (PreROD, ROD, Pulse).

annual patterns in each environmental attribute. Annual variation in the seasonal monthly component of flow volume was much more subdued and proportionally diverse in baseline PreROD flow-types compared to managed hydrographs. Managed flow-types exhibited a pattern of dramatic single spikes for flow volume, particularly in ROD flows followed by Pulse flows; a pattern not characteristic of baseline PreROD hydrographs (Figure 5A). In contrast, annual variation in the seasonal components of both water temperature attributes showed monthly spikes with: 1) greater variation, 2) more proportional diversity in secondary spikes, and 3) spikes with greater magnitude in managed flow-types relative to baseline PreROD hydrographs (Figure 5B and 5C).

Analysis of STL decomposition for the trend component also discovered conspicuous differences among flow-types for each environmental attribute. Not only did the magnitude in volume of flow and water temperature fluctuate dramatically but there were increased annual trends in both water temperature attributes in each managed flow-type hydrograph not observed in modeling of baseline flows (Figure 6; Table 4). For example, the trend component of flow volume exhibited a much more diversified annual pattern in baseline PreROD flow-types compared to managed hydrographs (Figure 6A). In contrast, annual trend components for both water temperature variables were more subdued in baseline flows relative to managed flow-types, with dramatic upward trends in maximum water temperature for ROD flows (2005 – 2011) and both water temperature attributes for Pulse flows (2012 – 2016; Figure 6B and 6C).

Lastly, STL decomposition of the remainder term for baseline flows showed that all environmental variables consisted of erratic monthly sequences with large positive and negative spikes. Such patterns are likely a reflection of stochastic annual flow and thermal regimes typical of seasonal climatic patterns unique to the region, which were not evident

**Table 4.** Results of GAM regression analyses of the Trend component produced by the Seasonal-Trend-Loess (STL) decomposition method for each environmental variable by flow-type; including average daily: flow volume (ADFV), maximum water temperature (MXWAT), and extreme variability in water temperature (ADWTV).

Variable	F-statistic	Ref.df.	p-value	R <sup>2</sup> .Adj.	Dev.Exp.	n
ADFV				0.141	23.3%	240
PreROD	13.1	2.0	< 0.000***			
ROD	11.9	2.0	< 0.000***			
Pulse	24.2	1.0	< 0.000***			
MXWAT						
PreROD	1.8	1.0	0.180	0.644	62.8%	240
ROD	0.8	1.6	0.360			
Pulse	137.6	2.0	< 0.000***			
ADWTV						
PreROD	4.2	2.0	< 0.016*	0.758	71.8%	240
ROD	41.0	1.5	< 0.000***			
Pulse	132.1	1.9	< 0.000***			

in highly regulated, and systematically and abruptly implemented managed hydrographs (Figure 7A – 7C). And, although STL seasonal and trend decomposition patterns were significantly correlated in most all hydrographs for each environmental variable, there were significance differences between hydrographs for each trend component for all variables, but not in seasonal or random components for any environmental attribute (Table 5). These results clearly indicate that the STL decomposition factor that defined the most conspicuous difference among flow-types for each environmental variable was the trend component.

### **Inter-quartile range (IQR) calculations**

Line and boxplot comparisons of each flow-type illustrate the significant and consistent quantitative differences along the 12-month continuum for each environmental variable described by STL decomposition models and the IQR analyses for each time series segment (Figure 8A – I). The seasonal term for the STL decomposition models showed that IQR values for flow volume in PreROD flows exceeded all other flow-types by a considerable margin. ROD flows showed the largest IQR value for maximum water temperature and Pulse flows had a considerably larger IQR value for extreme variability in water temperature (Table 6). For the trend component, STL decomposition models showed that Pulse flows had considerably larger IQR values for both water temperature variables than any other flow-type hydrograph. For the remainder term, STL decomposition models showed that baseline PreROD flows had the largest IQR value for flow volume consistent with a more random “natural” expression of the historical post-dam flow pattern prior to implementation of managed hydrographs in 2003. In contrast, the large IQR value for the remainder term in extreme variability in water temperature for Pulse flows was likely a byproduct of altered seasonal fluctuations observed in the trend data caused by manipulated hydrographs post-2003 (Figure 6B and 6C).

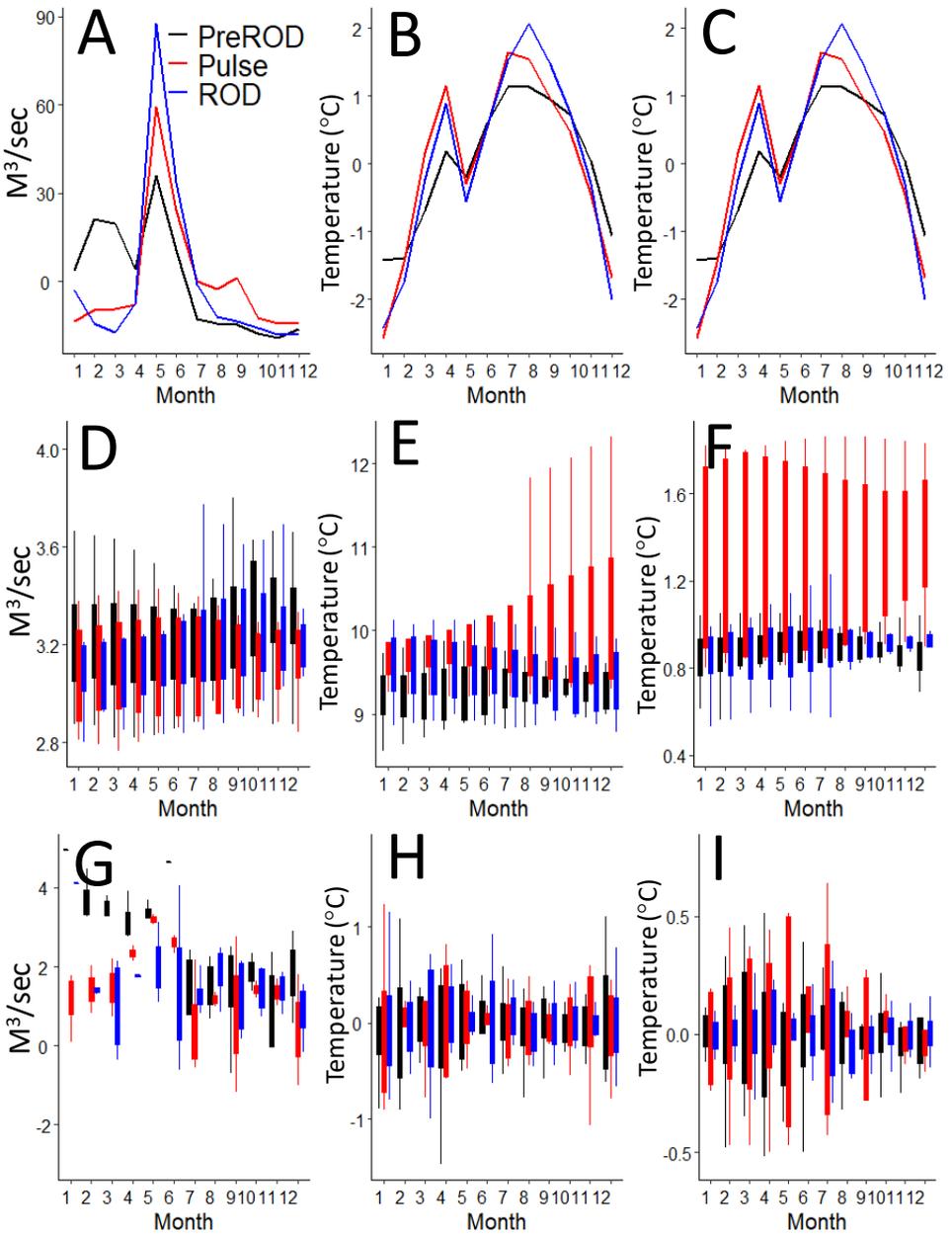
### **Time series**

Visual assessment of time series plots for PreROD and ROD flow-types showed that an additive model was most appropriate for each environmental attribute because variation remained relatively constant over time and did not depend on the level of the time series (Figure 3). However, results indicate that for Pulse flow hydrographs an additive model was not appropriate for describing variation in each water temperature variable because of the size and increasing annual trend in values amplified with the level of the time series (Figure 3B; Hyndman and Athanasopoulos 2018). In other words, seasonality in the thermal regime of Pulse flows at the beginning was small but became larger in later years. This pattern suggested that a multiplicative decomposition model for both water temperature variables was appropriate for the Pulse flow time series. Thus, in developing a follow-on time series model using SARIMA modeling for forecasting, both water temperature variables required a natural log transformation of the original data for Pulse flows (Hyndman and Athanasopoulos 2018).

Autocorrelation and partial autocorrelation functions examined for each environmental variable by flow-type revealed that each time series model was significantly non-stationary as there were numerous autocorrelations lying outside the 95% confidence limits for all environmental attributes (Figure 9). For each environmental variable, the range in Ljung-Box

**Table 5.** Kruskal-Wallis rank sum test ( $\chi^2$ ) and Spearman ranked correlation coefficients ( $r_s$ ) showing overall significance of each decomposition component (season, trend, random), followed by planned post-hoc Dunn test statistics (Z) for all pairwise comparisons between flow-types (PreROD [n = 94], ROD [n = 84], Pulse [n = 60]). Variables were average daily: ADFV = flow volume, 2) MXWAT = maximum water temperature, and 3) ADWTV = extreme variability in water temperature. All temperatures in degrees Celsius ( $^{\circ}\text{C}$ ) and volume of flow in  $\text{m}^3/\text{second}$ . Spearman rank correlation coefficients ( $r_s$ ) are below the diagonal and probabilities above the diagonal; p-values were  $< 0.05 = *$ ,  $< 0.01 = **$ ,  $< 0.001 = ***$ .

Decomposition components for season patterns									
Flow-type	ADFV			MXWAT			ADWTV		
	$\chi^2 = 7.3, \text{df} = 2, \text{p} = 0.030$			$\chi^2 = 0.0, \text{df} = 2, \text{p} = 1.000$			$\chi^2 = 0.4, \text{df} = 2, \text{p} = 0.830$		
Group(i)	Group(j)	Z	p-adj	Group(j)	Z	p-adj	Group(j)	Z	p-adj
PreROD	ROD	1.5	0.103	ROD	0.2	0.631	ROD	0.1	0.448
PreROD	Pulse	1.4	0.080	Pulse	0.2	1.000	Pulse	0.5	0.448
ROD	Pulse	2.7	0.010*	Pulse	0.1	0.477	Pulse	0.6	0.855
Spearman rank correlations ( $r_s$ ) for seasonal components									
Flow-type	PreROD	ROD	Pulse	PreROD	ROD	Pulse	PreROD	ROD	Pulse
PreROD	-----	0.001***	0.001***	-----	0.001***	0.001***	-----	0.001***	0.001***
ROD	0.571	-----	0.001***	0.950	-----	0.001***	0.750	-----	0.001***
Pulse	0.540	0.780	-----	0.910	0.970	-----	0.550	0.810	-----
Decomposition components for trend patterns									
Flow-type	ADFV			MXWAT			ADWTV		
	$\chi^2 = 10.6, \text{df} = 2, \text{p} < 0.001***$			$\chi^2 = 46.7, \text{df} = 2, \text{p} < 0.001***$			$\chi^2 = 48.1, \text{df} = 2, \text{p} < 0.001***$		
Group(i)	Group(j)	Z	p-adj	Group(j)	Z	p-adj	Group(j)	Z	p-adj
PreROD	ROD	1.8	0.0587	ROD	3.2	< 0.001***	ROD	1.5	0.062
PreROD	Pulse	3.2	0.002**	Pulse	6.8	< 0.001***	Pulse	6.8	< 0.001***
ROD	Pulse	1.6	0.056	Pulse	3.8	< 0.001***	Pulse	5.2	< 0.001***
Spearman rank correlations ( $r_s$ ) for trend components									
Flow-type	PreROD	ROD	Pulse	PreROD	ROD	Pulse	PreROD	ROD	Pulse
PreROD	-----	0.176	0.136	-----	0.002**	0.001***	-----	0.001***	0.495
ROD	0.150	-----	0.001***	-0.330	-----	0.001***	0.380	-----	0.801
Pulse	0.190	0.460	-----	-0.610	0.580	-----	-0.090	0.030	-----
Decomposition components for remainder patterns									
Flow-type	ADFV			MXWAT			ADWTV		
	$\chi^2 = 2.8, \text{df} = 2, \text{p} = 0.250$			$\chi^2 = 0.1, \text{df} = 2, \text{p} = 0.950$			$\chi^2 = 0.1, \text{df} = 2, \text{p} = 0.950$		
Group(i)	Group(j)	Z	p-adj	Group(j)	Z	p-adj	Group(j)	Z	p-adj
PreROD	ROD	1.5	0.199	ROD	0.3	1.000	ROD	0.1	0.609
PreROD	Pulse	1.3	0.144	Pulse	0.0	0.486	Pulse	0.2	0.465
ROD	Pulse	0.1	0.477	Pulse	0.2	0.615	Pulse	0.3	1.000
Spearman rank correlations ( $r_s$ ) for remainder components									
Flow-type	PreROD	ROD	Pulse	PreROD	ROD	Pulse	PreROD	ROD	Pulse
PreROD	-----	0.613	0.349	-----	0.745	0.389	-----	0.856	0.397
ROD	0.060	-----	0.484	0.040	-----	0.273	-0.020	-----	0.419
Pulse	-0.120	0.090	-----	-0.110	0.140	-----	-0.110	0.110	-----

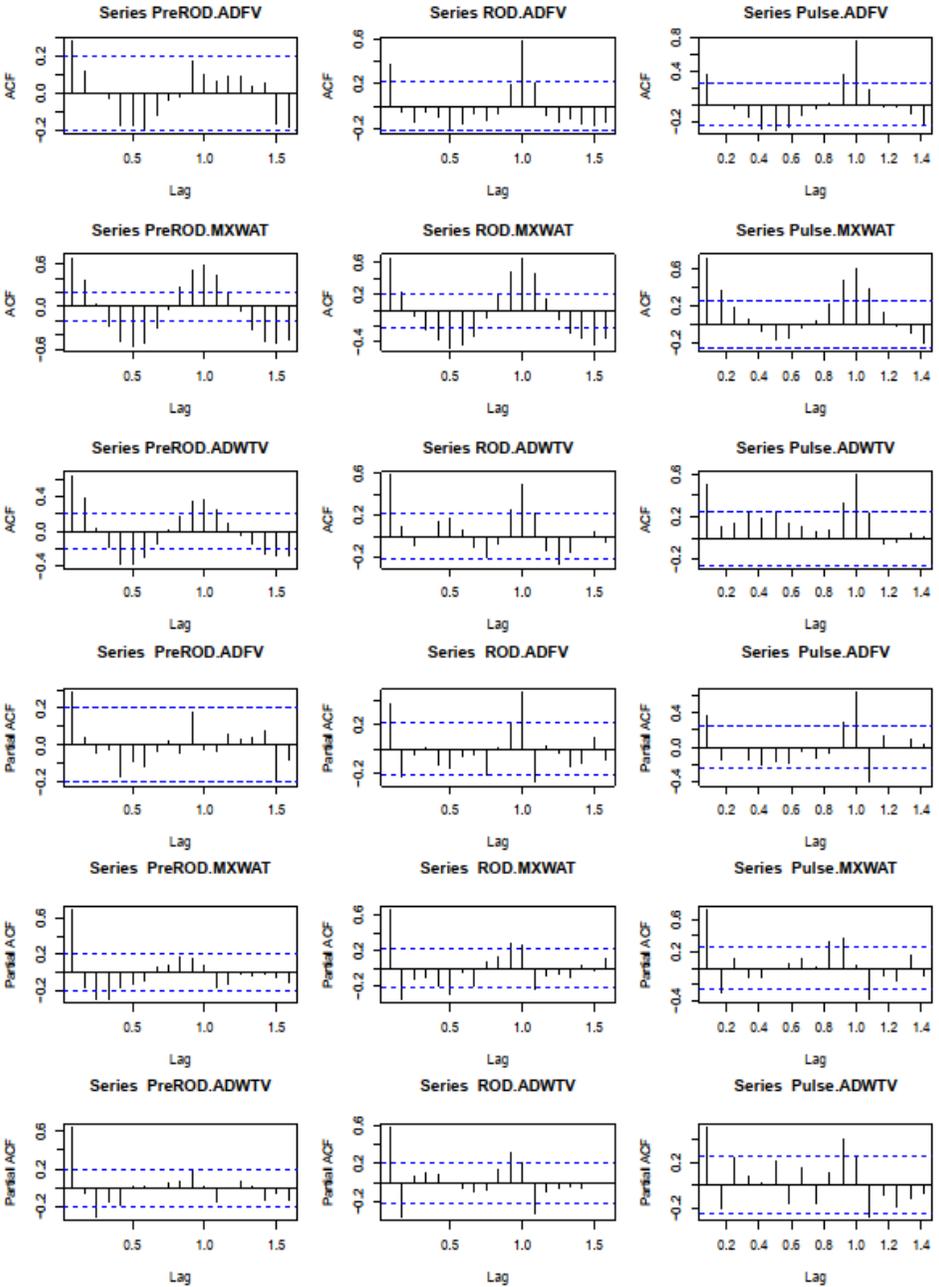


**Figure 8.** Line and box-plot comparisons of flow-types for each environmental variable based on the Seasonal-Trend-Loess (STL) decomposition analysis, which reflects the level of statistical significance presented in Table 4.

**Table 6.** Seasonal-Trend-Loess (STL) decomposition component summary of the computed interquartile range (IQR) of x-values, which measure how spread-out points were in the original time series data set for each environmental variable time series by flow-type. Variables were average daily: 1) ADFV = flow volume, 2) MXWAT = maximum water temperature, and 3) ADWTV = extreme variability in water temperature. All temperatures in degrees Celsius (°C) and volume of flow in m<sup>3</sup>/second. The higher the IQR the more spread-out the data points; the smaller the IQR the more aggregated the data points are around the mean. Right-hand bars on each STL plot were based on IQRs and allow a relative comparison of the magnitude of variation in each component.

Flow-type	Seasonal			Trend			Remainder (random)		
	1st Quartile	3rd Quartile	IQR	1st Quartile	3rd Quartile	IQR	1st Quartile	3rd Quartile	IQR
ADFV									
PreROD	-15.00	12.80	27.80	22.10	30.60	8.50	-15.80	7.10	22.90
ROD	-16.40	-2.60	13.70	20.50	27.40	6.90	-4.80	4.40	9.10
Pulse	-12.70	0.30	13.00	18.50	26.90	8.50	-4.00	4.60	8.60
MAXWAT									
PreROD	-0.79	0.78	1.56	9.03	9.56	0.53	-0.32	0.30	0.62
ROD	-0.86	1.03	1.89	9.11	9.79	0.69	-0.30	0.25	0.55
Pulse	-0.70	1.02	1.72	9.42	10.58	1.16	-0.33	0.24	0.57
ADWTV									
PreROD	-0.26	0.22	0.48	0.82	0.95	0.13	-0.13	0.12	0.25
ROD	-0.28	0.27	0.55	0.85	0.98	0.12	-0.08	0.08	0.16
Pulse	-0.52	0.41	0.94	0.90	1.75	0.85	-0.20	0.20	0.40

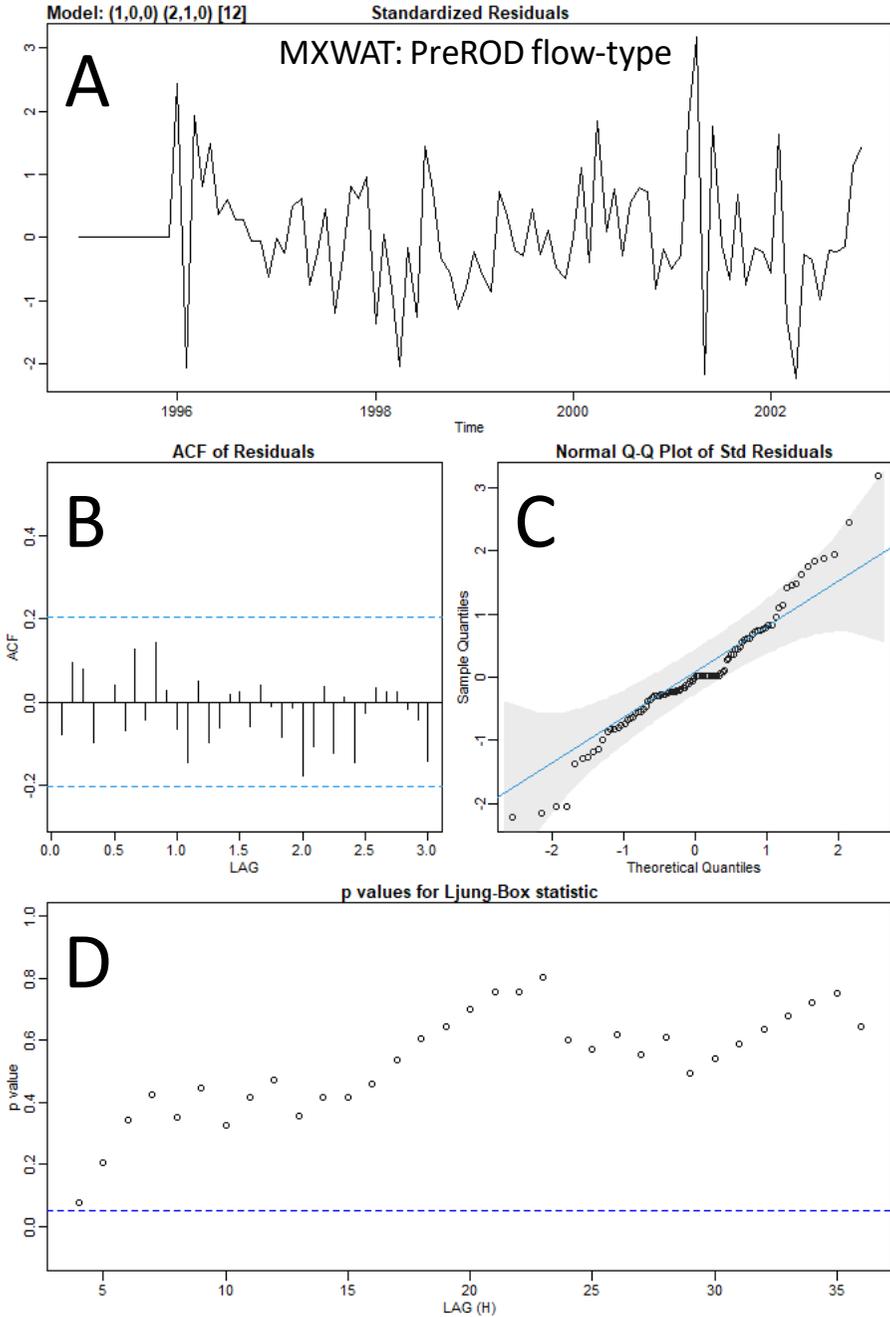
statistics were: 1) flow volume:  $\chi^2 = 8.0$  in PreROD flows ( $df = 1, p = 0.005$ ) to  $\chi^2 = 10$  in Pulse flows ( $df = 1, p = 0.003$ ); 2) maximum water temperature:  $\chi^2 = 50$  in PreROD flows ( $df = 1, p < 0.001$ ) to  $\chi^2 = 30$  in Pulse flows ( $df = 1, p < 0.001$ ); and 3) extreme variability in water temperature:  $\chi^2 = 40$  in PreROD flows ( $df = 1, p < 0.001$ ) to  $\chi^2 = 20$  in Pulse flows ( $df = 1, p < 0.001$ ). All variables by flow-type showed a slow decay at multiple lags of 12 suggesting coherent variance in the relationship indicative of monthly seasonal and cyclic variation in each environmental variable for all flow-types. These results support the earlier assertion of seasonality in each time series model necessitating the need for seasonal differencing with a period of 12. Therefore, rather than manually fitting by ARIMA modeling, best fit models for each flow-type time series were generated using the auto.arima function summarized in Table 7. Following this procedure Ljung-Box statistics indicated that none of the autocorrelations in the time series were different from zero and visual assessments showed that each time series model was stationary (Figure 10). All model parameters were then verified with a graphic illustration described above for each environmental variable grouped by flow-type (Table 7). These results provided no evidence to reject the hypothesis that the distribution of residuals in any of the time series models were not normal. Instead, for each flow-type the distribution of residuals for each environmental model was Gaussian (white noise), which: 1) statistically justified each proposed model, 2) demonstrated how an analysis of time series data may be done accurately, and 3) allowed continued processing of data with the ultimate goal of forecasting estimates of each environmental variable by flow-type using SARIMA.



**Figure 9.** Auto- and partial- autocorrelation functions (ACF, PACF) plots (correlograms) of raw data for averaged daily: flow volume (ADFV), maximum water temperature (MXWAT), and extreme variability in water temperature (ADWTW) by flow-type (PreROD, ROD, Pulse). Plot shows serial correlations that may change over time in each time series dataset where an error at one point in time travels to a subsequent point in time.

**Table 7.** Parameters used to evaluate the adequacy of each optimal ARIMA model for environmental variables by flow-type: 1) Akaike information criterion (AIC), 2) estimates for variance  $\sigma^2$  for different SARIMA models, 3) augmented Dicky-Fuller test (ADF), and 4) Box-Pierce tests ( $\chi^2$ ) determined if any group of autocorrelations of a time series were different from zero. Estimated variance and degrees of freedom (df) for each model are also provided.

Flow-type	Variable	Model	AIC -value	Estimate for $\sigma^2$	df	ADF test	Ljung-Box test ( $\chi^2$ )
PreROD	ADFV	(1,0,0) x (1,1,0) <sub>12</sub>	9.1	1,560.0	82	4.2, lag order = 4, p < 0.01	0.05, df = 1, p = 0.825
ROD	ADFV	(1,0,0) x (1,1,0) <sub>12</sub>	7.6	284.0	69	2.7, log order = 4, p = 0.27	0.01, df = 1, p = 0.916
Pulse	ADFV	(1,0,0) x (0,1,0) <sub>12</sub>	6.5	159.6	46	3.6, log order = 3, p = 0.04	< 0.01, df = 1, p = 0.998
PreROD	MXWAT	(1,0,0) x (2,1,0) <sub>12</sub>	2.0	0.5	80	4.1, lag order = 4, p < 0.01	0.63, df = 1, p = 0.427
ROD	MXWAT	(1,0,0) x (2,1,0) <sub>12</sub>	1.9	0.4	68	3.0, lag order = 4, p < 0.01	0.04, df = 1, p = 0.800
Pulse	MXWAT	(2,1,1) x (0,1,1) <sub>12</sub>	1.9	0.4	43	6.0, lag order = 3, p < 0.01	2.00, df = 1, p = 0.600
PreROD	ADWTV	(1,0,0) x (2,1,0) <sub>12</sub>	0.6	0.1	80	4.2, lag order = 4, p < 0.01	0.40, df = 1, p = 0.525
ROD	ADWTV	(1,0,0) x (2,1,1) <sub>12</sub>	0.1	0.0	67	4.0, lag order = 4, p < 0.01	2.00, df = 1, p = 0.200
Pulse	ADWTV	(1,0,1) x (0,1,0) <sub>12</sub>	0.8	0.1	45	3.0, lag order = 3, p < 0.01	0.09, df = 1, p = 0.764



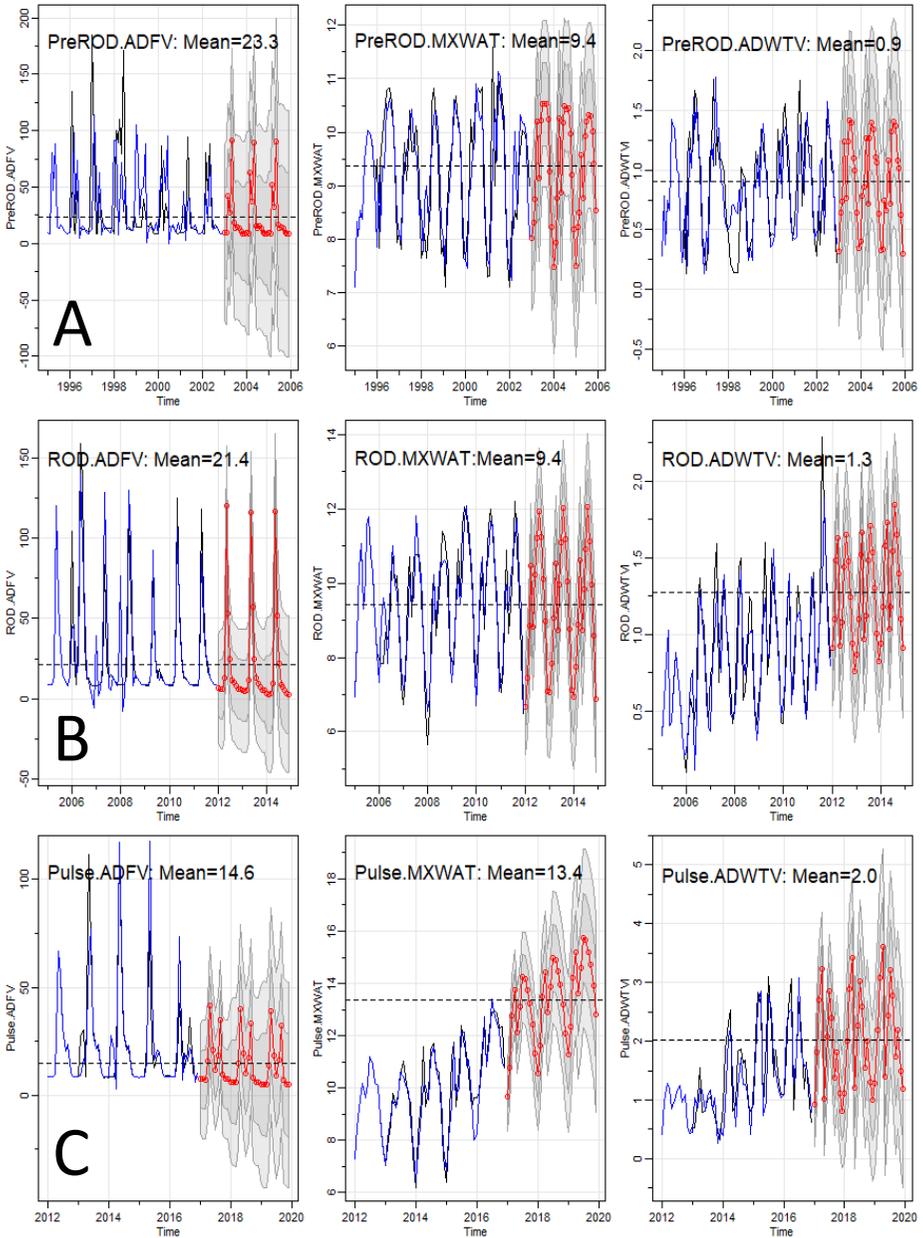
**Figure 10.** Graphic illustration of the adequacy of parameters used to estimate SARIMA models for each environmental variable using the PreROD flow-type as an example: A) differenced time series data; B) auto correlation function (ACF) plot of standardized residuals showing that all autocorrelations were close to zero as no lag exceeded confidence limits of  $p > 0.05$ ; C) normal Q-Q-plot of standardized residuals along with 95% confidence limits surrounding the diagonal of data points; and D) p-values for the Ljung-Box statistic.

## Forecasting using SARIMA

Analysis of the mean absolute percentage error showed that MAPE values for selected flow-type models were: 1) PreROD flow (flow volume = 81.7%, maximum water temperature = 4.9%, extreme variability in water temperature = 45.2%); 2) ROD flow (flow volume = 37.8%, maximum water temperature = 5.0%; extreme variability in water temperature = 15.0); and 3) Pulse flow (flow volume = 23.9%, maximum water temperature = 3.7%, extreme variability in water temperature = 20.0%). These empirical results signaled that the prediction derived from PreROD flow-types was poor for flow volume and extreme variability in water temperature relative to error estimates produced for ROD and Pulse flow hydrographs. This pattern was likely a reflection of the more stochastic nature of a “natural” post-dam and relatively unmanaged flow regime except under extreme flood conditions, which would be expected in a rare “Emergency of Dams” release, which is what happened in 1974. In contrast, error estimates for ROD and Pulse flows were considerably “better” as a reflection of the systematic and regular managed releases linked with anthropogenic hydrographs. The same explanation can also be applied to extreme variability in water temperature for managed flow-types, all of which appear reasonably good as models for each managed time series dataset. Conversely, prediction models based on maximum water temperature were all highly accurate (< 5.0% error). And the empirical results indicated that each model was able to accurately represent the baseline as well as each managed hydrograph time series model.

The predictive power of each SARIMA model was illustrated graphically by forecasting 36 months-ahead of the time series for each environmental variable by flow-type (Figure 11; Table 7). Overlapping blue lines for each “fitted” model (black lines) were substantial as predictions fit well to each time series dataset. Levels of prediction were calculated at 80% and 95% prediction confidence intervals as indicated by the light and dark shaded gray areas surrounding the red prediction line. Forecast values (red lines) were close to real values (black lines) and within the confidence intervals (grey shading). Thus, all monthly points plot very close to the actual prediction. In most models as time progresses beyond the first predicted point, uncertainty tends to increase, hence the prediction boundaries increase in amplitude. Importantly, follow-on forecasting of environmental variables for each flow-type over the next 3 years (36 months) showed: 1) that there were significantly different predictions among segmented flow-type time series; 2) the time span for each model was relatively long, and 3) results provided reasonably accurate predictions. Generally, forecasting further into the future will become less reliable particularly in a highly managed river system. Additionally, the fitted values for each forecast model were relatively close to the observed values. This means that the SARIMA models can be used to forecast future values because their forecasting accuracy is acceptable. Also, some lower predicted confidence limits, but not points, were negative for volume of flow, which is impossible for the flow of a river. In practice, confidences limit below zero are generally truncated when presenting them.

Consistent with graphic illustrations, SARIMA model predictions of future values over the next 36 months exhibited significant differences between flow-types in both the overall distribution of each environmental variable and in planned post-hoc paired comparisons of population mean ranks as reflected in mean values for each variable (Table 8). Noticeably for PreROD and ROD flow-types mean values of flow volume were greater than in Pulse flows, and projections of future ROD flows exceeded both other flow-types. Mean values of maximum water temperature for both PreROD and ROD flow-types were similar but the



**Figure 11.** Plots of future values based on SARIMA model forecasting of environmental variable values predicted for the next 36 months. Black colored lines are the original observed time series values and blue lines are the “fitted” values overlaid on top for comparison against the series itself. Means are given for each variable and their position on the graph indicated by a dashed black horizontal line. Dark gray shading represents 80% confidence intervals, light gray shading 95% confidence interval, and red lines and open circles represent predictions for future months. Temperature is found along the y-axis for each variable; A = PreROD flows, B = ROD flows, and C = Pulse flows for each environmental variable (ADVF = flow volume, MXWAT = maximum water temperature, ADWTV = extreme variability in water temperature).

**Table 8.** Kruskal-Wallis rank sum test ( $\chi^2$ ) and Spearman ranked correlation coefficients ( $r_s$ ) showing differences in forecasting 36-months into the future using predictions of SARIMA modeling illustrated in Figure 11, followed by post-hoc Dunn tests (Z) of all planned pairwise comparisons between flow-types (PreROD, ROD, Pulse). Variables were average daily: ADFV = flow volume, 2) MXWAT = maximum water temperature, and 3) ADWTV = extreme variability in water temperature. All temperatures in degrees Celsius ( $^{\circ}\text{C}$ ) and volume of flow in  $\text{m}^3/\text{second}$ . Spearman rank correlation statistics are found below the diagonal and probabilities above the diagonal;  $n = 36$  for all flow-type comparisons;  $p$ -values were  $< 0.05 = *$ ,  $< 0.01 = **$ ,  $< 0.001 = ***$ .

Flow-type	ADRV			MXWAT			ADWTV		
	$\chi^2 = 9.7, df = 2, p = 0.010$			$\chi^2 = 64.7, df = 2, p < 0.001***$			$\chi^2 = 42.4, df = 2, p < 0.001***$		
Group(i)	Group(j)	Z	p-adj	Group(j)	Z	p-adj	Group(j)	Z	p-adj
PreROD	ROD	3.0	0.004**	ROD	7.1	< 0.001***	ROD	3.2	0.001***
PreROD	Pulse	2.1	0.026*	Pulse	6.8	< 0.001***	Pulse	6.5	< 0.001***
ROD	Pulse	0.9	0.178	Pulse	0.3	0.380	Pulse	3.4	0.001**
Spearman rank correlation ( $r_s$ )									
Flow-type	PreROD	ROD	Pulse	PreROD	ROD	Pulse	PreROD	ROD	Pulse
PreROD	-----	0.001***	0.001***	-----	0.001***	0.001***	-----	0.001***	0.001***
ROD	0.660	-----	0.001***	0.940	-----	0.001***	0.750	-----	0.001***
Pulse	0.600	0.900	-----	0.770	0.820	-----	0.750	0.850	-----

range of variation in projected ROD flows (2006 – 2014) was greater than in future projections of PreROD flows (1995 – 2002). Width of confidence intervals in both flow-types tended to remain narrow throughout the predicted sequence of months, suggesting that the accuracy of the forecast for each PreROD and ROD flow-types effectively held over time through the prediction range.

In Pulse flows, however, not only was the mean and range of variation in maximum water temperature considerably greater than in other hydrographs, but an increasing trend was also evident based on dependent compounding effects of previous observations and errors. In extreme variability in water temperature the same overall pattern of flow-mediated variance was projected in both ROD and Pulse flow-types, which predicted trends of higher and increased extreme variation in water temperatures over the next 36 months, a pattern not seen in PreROD flow-type projections. Finally, width of confidence intervals in both managed flow types for each water temperature variable increased in future predictions as a direct function of greater variability associated with annually managed hydrographs. Generally, but not always, as the period between the date of a flow forecast and the actual forecast period narrows there also will be a corresponding reduction in model error.

### DISCUSSION

In this study we focused on time series analysis and forecasting seasonal river flow volume and water temperature using SARIMA modeling. Results show that use of subcomponents of the historical post-dam time series specific to managed flow-type hydrographs keyed to in-river geomorphologic restoration actions significantly misrepresented the: 1) time series characteristics, 2) seasonal-trend decomposition patterns, and 3) forecast accuracy compared to the baseline pre-restoration time series model. These results effectively nullify use of managed hydrographs in predicting future forecasts for flow-fish planning and

management purposes. Particularly revealing were significant differences in environmental time series data between flow-types in: 1) seasonal patterns among subcomponents of the historical hydrograph as illustrated in GAM regressions; 2) nonparametric methods; 3) STL decomposition analyses of season, trend, and random effects using both IQR values and nonparametric methods; and 4) future values of the thermal regime predicted by SARIMA forecasting

In virtually every comparison, managed flow-type hydrographs showed significant increases in maximum water temperature and extreme variability in water temperature. These patterns were particularly characteristic of Pulse flows relative to baseline PreROD flows. Grabowski et al. (2014) suggested that while small shifts in flow releases may be a function of climate change, major shifts usually reflect human interventions, with dam hydropeaking<sup>4</sup> being a distinct indicator of artificiality in the flow regime that impact monthly and daily flows (Greimel 2018). Such flow-effects equate roughly to the implementation of ROD flow hydrographs individually and in combination with companion Pulse flows into the upper mainstem of the Trinity River for geomorphic restoration purposes since 2003, due to longer in duration and volumetric proportion relative to individual pulsed flow augmentation releases.

Based on our results, we suggest that use of time series modeling and forecasting of seasonal trends in environmental data associated with large riverine systems without reference to continuous intrinsic periods within the historical time series model, where flow is anthropogenically manipulated, will be misleading when managers attempt to evaluate the overall characteristics and subsequent future forecasting that derive from such models. Results of our analysis have the potential to provide resource agencies with additional insight into strategic flow-mediated thermal planning that mimics a “natural” or regime standard for water temperature necessary to: 1) facilitate efficient use of water resources notwithstanding changing climate; and 2) prioritize management strategies and scheduling of flows for in-river restoration activity to increase efficiency in management of fisheries, aquatic habitat conservation, and water resources (Stanford et al. 1996; Poff et al. 1997; Fausch et al. 2002; Poole et al. 2004)

### **Time series and forecasting considerations**

The efficacy of these results suggests that time series analysis using SARIMA methodology is appropriate for modeling hydrological and water temperature data in the upper Trinity River in which the data exhibit autocorrelation with time in combination with semi-parametric regression (GAM). Application of linear models generally do not allow identification of nonlinear characteristics of hydrological data. This distinction is important when working with changes in the variance of environmental variables that fluctuate overtime, as their application may not be suited for modeling stochastic nonstationary data (Machiwal and Jha 2006; Nazir et al. 2018). River flow and other hydrologically-related variables frequently exhibit nonlinear behavior. In modeling, resource managers should consider both deterministic (algebraic) and stochastic parts of this parameter when making

<sup>4</sup> Hydropeaking is a unique form of flow regulation, in that it introduces frequent, short duration, artificial flow events to the river. The impacts of hydropeaking on channel size and morphology are highly dependent on the size and frequency of hydropeaks in relation to size of geomorphological effective flows prior to regulation. <http://wiki.reformrivers.eu/index.php/Hydropeaking>

appropriate decisions for the purpose of fish-flow and water resource management. These conditions also apply to regionally specific assessments of climate change. Conversely, use of nonlinear models, such as GAM in combination with the Box-Jenkins method, allow options for nonlinear modeling and consideration of autocorrelations among variables as well as lag-lead relationships between variables. Adding variable effects of reach-specific air temperature, water temperature, precipitation, or other auxiliary environmental co-variables using a multivariate approach to forecasting also will assist in attaining a solid presumption of a cause-effect relationship in historical time series analysis for flow and restoration managers to act upon.

Understanding variability and the limitations associated with management of riverine systems is essential for addressing the ever-increasing anthropogenic needs for water and the inescapable reality of climate change, which has advanced a theoretical construct known as “functional flows” (Zimmerman et al. 2020; CEFF 2020). This paradigm seeks to mimic natural flow regimes by incorporating regionally-specific ecological, geomorphic, and biogeochemical processes into a flow prescription that protects and supports relevant foundational physical and ecological processes, which it is hoped will sustain resident biological communities in some generally unknown, but viable capacity (Poff et al. 1997; CEFF 2020; Zimmerman et al. 2020). Increasingly, the extent of flow-mediated variance in water temperature also is a key component of regulations derived from valuations of water quality (Coutant 1999). Research focused on the implications of altered thermal variability can provide improved identification of conservation priorities, management of dam-derived hydropower, and sustainable fisheries management and restoration outcomes. Use of metrics that measure the extremes in thermal variance or evaluate the range of mean values rather than only the mean is also an important consideration in understanding variability in flow dynamics. This need is particularly relevant when evaluating the potential effects of short-duration pulsed flows, which have not received the attention needed regarding flow-fish effects (Sullivan and Hileman 2020).

Inevitably this approach will require accurate understanding of the underlying dynamics of riverine flow that may not be possible by use of statistical forecasting methods using conventional linear regression. River restoration and conservation planning would benefit from consideration of the natural temperature regime of riverine systems in their full complexity, rather than create predictions based on total temperature units delivered in a short period of time or at lethal thresholds (Poole et al. 2004; Steel et al. 2012; Romberger and Gwozdz 2018). Future climates will invariably differ from current climates with respect to thermal variance. Yet there is remarkably little research exploring these effects on individual or population-level fitness of in-river spawning anadromous salmonids or the complexity and dynamics of aquatic community food webs subjected to anthropogenic management of riverine flows in the Trinity River and elsewhere (Hughes and Murdoc 2017).

Forecasting outflow volume and temperature variability are essential tools for planning and management of dam operations as these activities directly influence the availability of water and the variability in the resulting thermal regimes created. Efforts to return natural variability to regional riverscapes through formation of a diverse mosaic of habitats within riverine and riverscape communities is a vital precursor to being realistic in our expectations of the range of possible restoration outcomes (Peipoch et al. 2015; Yarnell et al. 2015). Such efforts are irrespective of whether the goal is to: 1) re-naturalize flows and thermal regimes as a basis for understanding variability, uncertainty, and unpredictability in concert with

restoration initiatives; or 2) implementation of a functional flow design to address realistic anthropogenic needs for water resources, while simultaneously attempting to maintain the regional biotic and physical integrity of the riverscape. Thus, it is imperative to understand the dynamics of riverine flows over both historical and recent time scales as a prerequisite to restoration and effectiveness monitoring of our fisheries resources.

### **Resource management considerations**

Accurate forecasting of streamflow is a fundamental issue of interest to water resources engineers, hydrologists, and fisheries scientists. Identification of accurate and reliable analyses to model future river flow is an important precondition for successful planning and management of water resources upon which fisheries resources depend. From a practical perspective, use of reliable models to forecast river flow could be instrumental for regional fisheries management and water resources planning keyed to the upper Trinity River watersheds. Detection of trends and stationarity is a major focus of past hydrological and climatological time series analyses with a wide application of semi-parametric regression methods such as GAM. Yet forecasting highly accurate estimates of the volume and variability in the thermal regime of riverine flow remains problematic given the nonlinearity and uncertainty hidden in the historical data, which requires an approach with high forecasting precision and efficiency for effective application.

Future needs of water resource and fisheries management in the Trinity River would benefit significantly by placing environmentally-driven time series models into perspective relative anthropogenically-driven flow management hydrographs as part of flow-fish and river restoration management. Research designs that incorporate multivariate and dynamic conditional correlation methods would provide additional insights into the relationships between more “naturally” managed flow and thermal regimes relative to those forced upon the system by a highly manipulative anthropogenically-induced flow strategy (Pool 2004; Caissie 2006). In the Trinity River managed flows have not been mirrored historical regional hydrographic patterns linked to upland watersheds of the Trinity River and Klamath Basin. Such considerations need to be fully vetted with the overarching management goals of flow-mediated hydrographs designed to mimic an “unimpeded”, “natural”, e-flow, or “functional” flow post-dam management strategy (Yarnell et al. 2015), while simultaneously accommodating riverine: 1) thermal criteria, 2) in-river restoration, 3) conservation of biotic communities, and 4) water conservation policies unique to the particular river system in northern California and elsewhere.

Palmer and Ruhi (2019) correctly state that effective river restoration requires advancing our mechanistic understanding of how flow regimes affect biota and ecosystem processes. Any attempt to derive insight into sustainable flow-fish management strategies for hatchery- and natural-area spawning salmonids based on time series modeling of post-2003 ROD or Pulse hydrology will be less reliable than those based on long-term data collected simultaneously from: 1) unobstructed headwaters of the Trinity River above the Trinity Reservoir in combination with 2) the primary free flowing tributaries of the mainstem Trinity River below Lewiston Dam. A prerequisite to management of riverine systems should be the incorporation of these kinds of “baseline” data into long-term restoration strategies coincidental with natural and historical events that shape the regions riverine hydrology to which life histories of resident salmonids have adapted. Distinguishing these elements in flow management could help managers restore ecologically important facets of the flow regime.

We recommend that in projecting future flow conditions, restoration managers should consider use of environmental information that optimizes the operational time span of continuous uninterrupted and sequential collection of data to be as long-term as possible. Reliable predictions may be obtained over relatively shorter time spans by continuous operation, monitoring, and data gathering at gauging stations within the focal reach (Papalaskaris and Kampas 2017). Sequentially, the most accurate and complete data records come from river gauging stations, followed by supplemental information obtained from remotely sensed data and documentary sources (Grabowski et al. 2014). Numerous indicators may be extracted from river flow records (e.g., average, extreme flows, and their timing) and used to estimate hydrological alteration. Gauging station records minimally spanning several decades (e.g.  $\geq 30$  years) are typically necessary for this type of analysis. This approach will allow the entire historical time series can be analyzed to investigate temporal trends, in magnitude, frequency, timing, duration, and rate of change in the flow-dynamic (Grabowski et al. 2014).

Further, flows can be subdivided into time periods related to significant changes in the historical flow regime (e.g., baseline pre-dam construction, post-dam construction, in-river restoration flows, or fish-flows). Subdivided flows can also be applied to an “unimpeded”, “natural”, e-flow, “functional” flow post-dam management strategy, or other prescriptions attributable to natural flow abstractions. For the upper Trinity River, the post-dam “natural” riverine environment evaluated by the STL modeling using annual flow and thermal variance attributes was illustrated in the seasonal, trend, and remainder patterns of monthly variation produced by baseline PreROD flow-type models. However, we caution that use of subdivided historical raw data can result in loss of detail, resolution, and therefore information content when partitioning monthly data compared to use of Julian weeks or a daily schedule. Clearly, results of our study would have been benefited had the data been detailed enough to accommodate smaller subdivisions.

Once established, data can be feed into a standardized modeling procedure as additional raw data becomes available to develop a more accurate and reliable long-term model for use in monitoring seasonal variation in flow-fish thermal regimes (Grabowski et al. 2014). These datasets will facilitate annual: 1) monitoring, modeling, and gaming of hydrological conditions; 2) monitoring of riverine thermal regimes for use in flow-fish management, assessment of in-river fitness metrics (fertility, productivity) for both hatchery- and natural-area spawning salmonids in cooperation and coordination with hatchery operations; 3) facilitate scheduling of specific river restoration actions; and 4) permit annual monitoring and assessment of climate change effects within the mainstem of Trinity River in support of the above management recommendations.

In conclusion, time series modeling and forecasting with flow and thermal data developed during the period of managed hydrographs (post-2003) will greatly detract from the ability to accurately predict future thermal regimes in the upper Trinity River. Sustainable flow-fish management for hatchery- and natural-area spawning salmonids should consider watershed and unobstructed tributary characteristics in assessing the impacts to resident salmonids, which automatically incorporate the annual effects of climate change on riverine systems within the greater Trinity Basin. Time series modeling using such criteria would facilitate development of a flow management strategy for river restoration that fit the historical characteristics of the regional watershed while simultaneously accommodating management of fisheries and other aquatic resources experiencing changing climatic conditions now and into the future.

## ACKNOWLEDGEMENTS

We thank Robert Nau (Duke University) for discussions of the use of consecutive sequence versus disjunct sequences in the time series analysis of managed flows. We are also grateful for the editorial comments and suggestions from several anonymous reviewers.

## LITERATURE CITED

- Adeloye, A. J., and M. Montaseri. 2002. Preliminary streamflow data analyses prior to water resources planning study. *Hydrological Sciences Journal* 47:679–692.
- Akaike, H. 1973. Information theory and an extension of the maximum likelihood principle. Pages 267–281 in B. N. Petrov and F. Csáki, editors. 2nd International Symposium on Information Theory, Tsahkadsor, Armenia, Budapest, USSR.
- Attar, N. F., Q. B. Pham, S. F. Nowbandegani, M. Rezaie-Balf, C. M. Fai, A. N. Ahmed, S. Pipelzadeh, T. D. Dung, P. T. T. Nhi, D. N. Khoi, and A. El-Shafie. 2020. Enhancing the prediction accuracy of data-driven models for monthly streamflow in Urmia Lake Basin based upon the autoregressive conditionally heteroskedastic time-series model. *Applied Science* 10:1-20. Available from: <http://www.mdpi.com/journal/applsci>
- Bari, S. H., M. T. Rahman, M. M. Hussain, and S. Ray. 2015. Forecasting monthly precipitation in Sylhet City using ARIMA model. *Civil and Environmental Research* 7:69–77.
- Benjamini, Y., and Y. Hochberg. 2000. On the adaptive control of the false discovery rate in multiple testing with independent statistics. *Journal of Educational and Behavioral Statistics* 25:60–83.
- Box, G. E. P., and G. M. Jenkins. 1976. *Time series analysis: forecasting and control*. Holden-Day, San Francisco, CA, USA.
- Brownlee, J. 2018. How to create an ARIMA model for time series forecasting in Python. *Machine Learning Mastery*. Available from: <https://machinelearningmastery.com/arima-for-time-series-forecasting-with-python/>
- Burnham, K. P., and D. R. Anderson. 1998. *Model selection and inference: a practical information-theoretic approach*. Springer-Verlag, New York, NY, USA.
- Caissie, D. 2006. The thermal regime of rivers: a review. *Freshwater Biology* 51:1389–1406.
- California Department of Water Resources (DWR). 2020. California Department of Water Resources Data Exchange Center. Available from: <http://cdec.water.ca.gov>
- California Environmental Flows Framework (CEFF). 2020. Functional flows approach. Available from: <https://ceff.sf.ucdavis.edu/functional-flows-approach>
- Carter, J. L., V. H. Resh, D. M. Rosenberg, and T. B. Reynoldson. 2006. Biomonitoring in North American rivers: a comparison of methods used for benthic macroinvertebrates in Canada and the United States. Pages 203–228 in G. Ziglio, G. Flaim, M. Sillgardi, eds. *Biological Monitoring of Rivers*. John Wiley and Sons Ltd, New York, NY, USA.
- Casella, G., and R. L. Berger. 2002. *Statistical Inference*. Duxbury, Pacific Grove, CA, USA.
- Chatfield, C., and H. Xing. 2019. *The analysis of time series an introduction with R*. 7th edition. Chapman and Hall/CRC, London, UK.

- Cleveland, R. B., W. S. Cleveland, J. E. McRae, and I. Terpenning. 1990. STL: a seasonal-trend decomposition procedure based on Loess. *Journal of Official Statistics* 6:3–73.
- Cleveland, W. S., E. Grosse, and W. M. Shyu. 1992. Local regression models. Pages 309–376 in J. M. Chambers and T. Hastie, editors. *Statistical Models*. S. Chapman and Hall, New York, NY, USA.
- Corder, G. W., and D. I. Foreman. 2014. *Nonparametric statistics: A step-by-step approach*, John Wiley and Sons, Inc., Hoboken, NJ, USA.
- Coutant, C. C. 1999. Perspective on temperature in the Pacific Northwest's fresh water. Environmental Sciences Division, Publication No. 4849, Oak Ridge National Laboratory, TN, USA.
- Cox, D. R., and H. D. Miller. 1977. *The theory of stochastic processes*. 1st edition. Chapman and Hall/CRC, Boca Raton, FL, USA.
- Diankha, O., and M. Thiaw. 2016. Studying the ten years variability of *Octopus vulgaris* in Senegalese waters using generalized additive model (GAM). *International Journal of Fisheries and Aquatic Studies* 2016:61–67.
- Everitt, B. S., and T. Hothorn. 2011 *An introduction to applied multivariate analysis with R*. Springer, New York, NY, USA.
- Fausch, K. D., C. E. Torgersen, C. V. Baxter, and H. W. Li. 2002. Landscapes to riverscapes: Bridging the gap between research and conservation of stream fishes. *BioScience* 52: 483–498.
- Fuller, W. A. 1976. *Introduction to Statistical Time-series*. John Wiley and Sons, New York, NY, USA.
- Grabowski, R. C., N. Surian, and A. M. Gurnell. 2014. Characterizing geomorphological change to support sustainable river restoration and management. *WIREs Water* 1:483–512. doi: 10.1002/wat2.1037. Available from: [https://www.academia.edu/7772927/Characterizing\\_geomorphological\\_change\\_to\\_support\\_sustainable\\_river\\_restoration\\_and\\_management?email\\_work\\_card=view-paper](https://www.academia.edu/7772927/Characterizing_geomorphological_change_to_support_sustainable_river_restoration_and_management?email_work_card=view-paper)
- Greimel, F., L. Schülting, W. Graf, E. Bondar-Kunze, S. Auer, B. Zeiringer, and C. Hauer. 2018. Hydropeaking impacts and mitigation. Pages 91–110 in S. Schmutz and J. Sendzimir editors. *Riverine Ecosystem Management: Science for Governing Towards a Sustainable Future*. Aquatic Ecology Series 8. Springer Open, Cham, Switzerland.
- Hallock, R. J., R. F. Elwell, and D. H. Fry. 1970. Migrations of adult king salmon, *Oncorhynchus tshawytscha*, in the San Joaquin Delta, as demonstrated by use of sonic tags. *California Fish and Game Bulletin* 151.
- Hastie, T., and R. Tibshirani. 1990. Generalized additive models. *Statistical Science* 1:297–301.
- Hildebrand, M., and G. E. Goslow. 2001. *Analysis of vertebrate structure*. Wiley, New York, NY, USA.
- Hill, T., and P. Lewicki. 2007. *Statistics: methods and applications*. StatSoft, Tulsa, OK, USA.
- Holčík, J. 1996. Ecological fish production in the inland delta of the Middle Danube, a floodplain river. *Environmental Biology of Fishes* 46:151–165.
- Hughes, M. S., and Murdoch A. R. 2017. Spawning habitat of hatchery spring Chinook Salmon and possible mechanisms contributing to lower reproductive success. *Transactions of the American Fisheries Society* 146:1016–1027.

- Hyndman, R. J., and Y. Khandakar. 2008. Automatic time series forecasting: The forecast package for R. *Journal of Statistical Software* 26.
- Hyndman, R. J., and G. Athanasopoulos. 2018. *Forecasting: Principles and Practice*. 2nd edition. OTexts, Melbourne, Australia.
- Lewis, C. D. 1982. *Industrial and Business Forecasting Methods*. Butterworths, London, UK.
- Ljung, G. M., and G. E. P. Box. 1978. On a measure of lack of fit in time series models. *Biometrika* 65:297–303.
- Machiwal, D., and M. K. Jha. 2006. Time series analysis of hydrological data for water resources planning and management: a review. *Journal of Hydrology and Hydro-mechanics* 54:237–257.
- Madsen, H., and P. Thyregod. 2011 *Introduction to General and Generalized Linear Models*. Chapman and Hall/CRC, Boca Raton, FL, USA.
- Magneson, M. D., and C. D. Chamberlain. D. 2014. The influence of Lewiston Dam releases on water temperatures of the Trinity River and Lower Klamath River, CA, April to October 2014. U.S. Fish and Wildlife Service, Arcata Fish and Wildlife Office, Arcata Fisheries Data Series Report Number DS 2015-41, Arcata, California. Available from: [https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=4&cad=rja&uact=8&ved=2ahUKEwjtvbXw\\_o7gAhWsCTQIHVTQA ccQFjADegQIBxAC&url=http%3A%2F%2Fodp.trrp.net%2FDataPort%2Fdoc.php%3Ffid%3D2211&usg=AOvVaw16FSHoaPjluYNVZA5yWnJ9](https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=4&cad=rja&uact=8&ved=2ahUKEwjtvbXw_o7gAhWsCTQIHVTQA ccQFjADegQIBxAC&url=http%3A%2F%2Fodp.trrp.net%2FDataPort%2Fdoc.php%3Ffid%3D2211&usg=AOvVaw16FSHoaPjluYNVZA5yWnJ9)
- Makridakis, S., S. Wheelwright, and V. McGee. 1983. *Forecasting Methods and Applications*. 2nd edition. Wiley and Sons, New York, NY, USA.
- Martínez-Acosta, L., J. P. Medrano-Barboza, Á. López-Ramos, J. F. R. López, and A. A. López-Lambrano. 2020. SARIMA approach to generating synthetic monthly rainfall in the Sinú River watershed in Colombia. *Atmosphere* 112:16.
- McCullough, D. A. 1999. A review and synthesis of effects of alterations to the water temperature regime on freshwater life stages of salmonids, with special reference to Chinook Salmon. Seattle, Washington, U.S. Environmental Protection Agency, Region 10. Available from: <https://www.critfc.org/blog/reports/a-review-and-synthesis-of-effects-of-alterations-to-the-water-temperature-regime-on-freshwater-life-stages-of-salmonids-with-special-reference-to-chinook-salmon/>
- McDonald, J. H. 2014. *Handbook of biological statistics*. Sparky House Publishing, Baltimore, MD, USA.
- Moreno, J. J., M. Moreno, A. P. Pol, A. S. Abad, and B. C. Blasco. 2013. *Psicothema* 4:500–506. Available from: [https://www.researchgate.net/publication/257812432\\_Using\\_the\\_R-MAPE\\_index\\_as\\_a\\_resistant\\_measure\\_of\\_forecast\\_accuracy](https://www.researchgate.net/publication/257812432_Using_the_R-MAPE_index_as_a_resistant_measure_of_forecast_accuracy).
- Nau R. 2017. ARIMA models for time series forecasting. Available from: <https://people.duke.edu/~rnau/seasarim.htm>
- Nazir, H. M., I. Hussain, I. Ahmad, M. Faisal, and I. M. Almanjahie. 2018. An improved framework to predict river flow time series data. *PeerJ* 7:1–22.
- Nychka. 1988. Bayesian confidence intervals for smoothing splines. *Journal of the American Statistical Association* 83:1134–1143.
- Olden, J. D., and R. J. Naiman 2010. Incorporating thermal regimes into environmental flows assessments: modifying dam operations to restore freshwater ecosystem integrity. *Freshwater Biology* 55:86–107.

- Pajuelo, J. G., and J. M. Lorenzo. 1995. Analysis and forecasting of the demersal fishery of the Canary Islands using an ARIMA model. *Scientia Marina* 59:155–164.
- Palmer, M., and A. Ruhi. 2019. Linkages between flow regime, biota, and ecosystem processes: implications for river restoration. *Science* 20:9–20.
- Papalaskaris, T., T. Panagiotidis, and A. Pantrakis. 2016. Stochastic monthly rainfall time series analysis, modeling and forecasting in Kavala city, Greece, North-Eastern Mediterranean Basin. *Procedia Engineering* 162:254–263.
- Papalaskaris, T., and G. Kampas. 2017. Time series analysis of water characteristics of streams in Eastern Macedonia–Thrace, Greece. *European Water* 57:93–100.
- Peipoch, M., M. Brauns, F. R. Hauer, M. Weitere, and H. M. Valett. 2015. Ecological simplification: human influences on riverscape complexity. *BioScience* 65:1057–1065.
- Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegard, B. D. Richter, R. E. Sparks, and J. Stromberg. 1997. The natural flow regime: a paradigm for riverine conservation and restoration. *Bioscience* 47:769–784.
- Poole, G. C., J. B. Dunham, D. M. Keenan, S. T. Sauter, D. A. McCullough, C. Mebane, J. C. Lockwood, D. A. Essig, M. P. Hicks, D. J. Sturdevant, E. J. Materna, S. A. Spalding, J. Risley, and M. Deppman. 2004. The case for regime-based water quality standards. *BioScience* 159:155–161.
- Prasad, A. 2019. Prediction and analysis of time series data using tensorflow. *Towards Data Science*, 15 November. Available from: <https://towardsdatascience.com/prediction-and-analysis-of-time-series-data-using-tensorflow-2136ef633018>
- R Core Team. 2020. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. Available from: <http://www.R-project.org>
- Romberger, C. Z., and S. Gwozdz. 2018. Performance of water temperature management on the Klamath and Trinity Rivers, 2017. U.S. Fish and Wildlife Service. Arcata Fish and Wildlife Office, Arcata Fisheries Data Series Number DS 2018-59, Arcata, California. Available from: <https://www.fws.gov/arcata/fisheries/reports/dataSeries/2017%20Klamath-Trinity%20water%20temp%20reportFINALWith-Appdex.pdf>
- Salas, J. D. 1993. Analysis and Modeling of Hydrologic Time Series. Pages 19.1–19.72 in D. R. Maidment, editor. *Handbook of Hydrology*, McGraw-Hill, Inc, New York, NY, USA.
- Shibatani, R. 2020. Commentary: the final demise of unimpaired flows. *Maven's Notebook*, January 2020. Available from: <https://mavensnotebook.com/2020/01/28/robert-shibatani-commentary-the-final-demise-of-unimpaired-flows/>
- Shumway, R. H., and D. S. Stoffer. 2017. Data sets and scripts to accompany time series analysis and its applications: with R examples. *Springer Texts in Statistics*. Springer, New York, NY, USA.
- Stanford, J. A., J. V. Ward, W. J. Liss, C. A. Frissell, R. N. Williams, J. A. Lichatowich, and C. C. Coutant. 1996. A general protocol for restoration of regulated Rivers. United States Department of Energy Publications 43. Available from: <https://digitalcommons.unl.edu/usdoepub/43>
- Steel, E. A., A. Tillotson, D. A. Larsen, A. H. Fullerton, K. P. Denton, and B. R. Beckman. 2012. Beyond the mean: the role of variability in predicting ecological effects of stream temperature on salmon. *Ecosphere* 3:104.

- Stephens, M. A. 1979. Test of fit for the logistic distribution based on the empirical distribution function. *Biometrika* 66:591–5.
- Stergiou, K. I. 1991. Short-term fisheries forecasting comparison of smoothing, ARIMA and regression techniques. *Journal of Applied Ichthyology* 7:193–204.
- Stergiou, K. I., E. D. Christou, and G. Petrakis. 1997. Modelling and forecasting monthly fisheries catches: comparison of regression, univariate and multivariate time series methods. *Fisheries Research* 29:55–95.
- Sullivan, R. M., and J. P. Hileman. 2018. Annual and seasonal variation, relative abundance, and effects of managed flows on timing of migration in Brown Trout (*Salmo trutta*) in the upper Trinity River. *California Fish and Game* 104:99–128.
- Sullivan, R. M., and J. P. Hileman. 2019. Effects of managed flows on Chinook Salmon in relation to run-timing, average annual percent fertility, and fluctuations in water temperature and flow volume. *California Fish and Game* 105:132–176.
- Sullivan, R. M., and J. P. Hileman. 2020. Comparative analyses of upstream migration in a multispecies assemblage of fish in response to highly managed flow regimes. *California Fish and Wildlife* 106:99–138.
- Trinity River Flow Evaluation Study (TRFES). 1999. Report by the U.S. Fish and Wildlife Service and Hoopa Valley Tribe to the Secretary, U.S. Department of Interior, Washington, D.C. Available from: [https://www.fws.gov/arcata/fisheries/reports/technical/Trinity\\_River\\_Flow\\_Evaluation\\_-\\_TOC.pdf](https://www.fws.gov/arcata/fisheries/reports/technical/Trinity_River_Flow_Evaluation_-_TOC.pdf)
- Trinity River Restoration Program (TRRP). 2020. Trinity River Restoration Program website. Available from: <http://www.trrp.net>
- Tsiatis, A. A. 2006. Semiparametric theory and missing data. Springer Series in Statistics. Springer, New York, NY, USA.
- United States Bureau of Reclamation (USBR). 2000. U.S. Department of the Interior. Record of Decision Trinity River Mainstem Fishery Restoration Final Environmental Impact Statement/Environmental Impact Report, December 2000. Available from: <http://odp.trrp.net/library/document/?id=227>
- Wang, X., K. S. Smith, and R. J. Hyndman. 2006. Characteristic-based clustering for time series data. *Data Mining and Knowledge Discovery* 13:335–364.
- Wissmar, R. C., and P. A. Bisson. 2003. Strategies for restoring river ecosystems: sources of variability and uncertainty in natural and managed Systems. American Fisheries Society, Bethesda, MD, USA.
- Woelfle-Erskine, C., A. C. Wilcox, and J. N. Moore. 2012. Combining historical and process perspectives to infer ranges of geomorphic variability and inform river restoration in a wandering gravel-bed river. *Earth Surface Processes and Landforms* 37:1302–1312.
- Wood, S. N. 2017. Generalized additive models: an introduction with R. 2nd edition. Chapman and Hall/CRC, Boca Raton, FL, USA.
- Yarnell, S. M., G. E. Petts, J. C. Schmidt, A. A. Whipple, E. E. Beller, C. N. Dahm, P. Goodwin, and J. H. Viers. 2015. Functional flows in modified riverscapes: hydrographs, habitats, and opportunities *BioScience* 65:963–972.
- Zar, J. H. 2010. Biostatistical analysis. Prentice-Hall, Upper Saddle River, NJ, USA.
- Zimmerman, J., J. Howard, J. Rosenfield, and R. Henery. 2020. Guest commentary (rebuttal): ecologists see little difference between unimpaired and (truly) functional approaches to flow. *Maven's Notebook*, February 2020. Available from: <https://>

[mavensnotebook.com/2020/02/04/guest-commentary-rebuttal-ecologists-see-little-difference-between-unimpaired-and-truly-functional-approaches-to-flow/](https://mavensnotebook.com/2020/02/04/guest-commentary-rebuttal-ecologists-see-little-difference-between-unimpaired-and-truly-functional-approaches-to-flow/) and <https://ceff.sf.ucdavis.edu/functional-flows-approach>

*Submitted 4 May 2020*

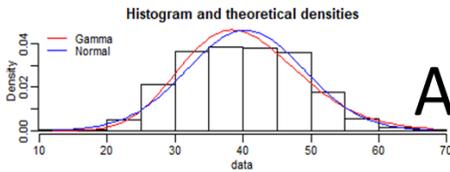
*Accepted 22 September 2020*

*Associate Editors were L. Damon and J. Kelly*

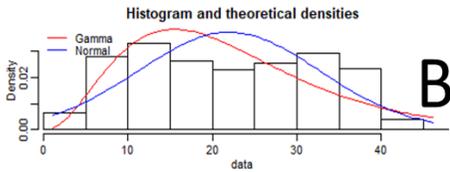
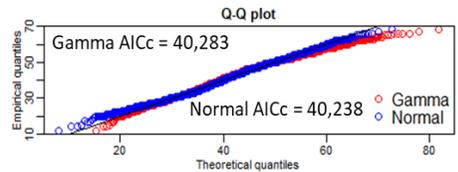
## APPENDIX I

Year	Water year type	Flow-type	Natural flow at Lewiston Dam (km <sup>3</sup> )	TRRP restoration release (km <sup>3</sup> )	Lewiston Reservoir management releases (km <sup>3</sup> )	Ceremonial releases (km <sup>3</sup> )	Other releases (km <sup>3</sup> )	Trinity River total release (km <sup>3</sup> )	Trinity River peak rate release (m <sup>3</sup> /sec)	Diversion to Central Valley (km <sup>3</sup> )
2001	Dry	PreROD	1.009	0.468	0.000	0.005	0.000	0.473	60,598	0.825
2002	Normal	PreROD	1.595	0.595	0.000	0.000	0.000	0.595	186,042	0.776
<b>Total</b>			<b>2.604</b>	<b>1.063</b>	<b>0.000</b>	<b>0.005</b>	<b>0.000</b>	<b>1.068</b>	<b>246,640</b>	<b>1.601</b>
<b>Average</b>			<b>1.302</b>	<b>0.532</b>	<b>0.000</b>	<b>0.003</b>	<b>0.000</b>	<b>0.534</b>	<b>123,320</b>	<b>0.800</b>
2005	Wet	ROD	1.820	0.798	0.000	0.004	0.000	0.803	216,341	0.575
2006	Ext Wet	ROD	3.078	0.999	0.501	0.000	0.000	1.500	294,495	1.665
2007	Dry	ROD	0.928	0.559	0.000	0.005	0.000	0.564	136,204	0.758
2008	Dry	ROD	1.079	0.800	0.000	0.000	0.000	0.800	195,103	0.684
2009	Dry	ROD	1.029	0.549	0.000	0.014	0.000	0.563	131,107	0.665
2010	Wet	ROD	1.976	0.810	0.000	0.000	0.000	0.810	222,004	0.339
2011	Wet	ROD	2.322	0.890	0.000	0.013	0.000	0.903	348,297	0.583
2017	Ext Wet	ROD	2.872	1.013	0.044	0.011	0.000	1.068	339,802	0.775
2019	Wet	ROD	2.092	0.867	0.000	0.010	0.000	0.877	305,822	0.523
<b>Total</b>			<b>17,194</b>	<b>7,285</b>	<b>0.545</b>	<b>0.058</b>	<b>0.000</b>	<b>7.888</b>	<b>2189,175</b>	<b>6.568</b>
<b>Average</b>			<b>1.910</b>	<b>0.809</b>	<b>0.061</b>	<b>0.006</b>	<b>0.000</b>	<b>0.876</b>	<b>243,242</b>	<b>0.730</b>
2003	Wet	Pulse	2.304	0.553	0.084	0.007	0.042	0.686	78,721	1.057
2004	Wet	Pulse	1.864	0.803	0.100	0.000	0.045	0.947	179,812	1.218
2012	Normal	Pulse	1.326	0.798	0.000	0.000	0.048	0.846	174,998	0.875
2013	Dry	Pulse	1.052	0.557	0.000	0.012	0.023	0.592	129,974	1.051
2014	Crit Dry	Pulse	0.489	0.457	0.000	0.000	0.080	0.537	97,976	0.763
2015	Dry	Pulse	1.109	0.556	0.000	0.011	0.059	0.626	250,038	0.555
2016	Wet	Pulse	1.797	0.874	0.000	0.000	0.048	0.922	271,842	0.344
2018	Crit Dry	Pulse	0.674	0.465	0.000	0.000	0.042	0.507	57,766	0.481
<b>Total</b>			<b>10,615</b>	<b>5,062</b>	<b>0.184</b>	<b>0.031</b>	<b>0.387</b>	<b>5.664</b>	<b>1241,127</b>	<b>6.344</b>
<b>Average</b>			<b>1.327</b>	<b>0.633</b>	<b>0.023</b>	<b>0.004</b>	<b>0.048</b>	<b>0.708</b>	<b>155,141</b>	<b>0.793</b>

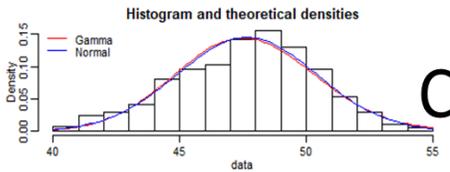
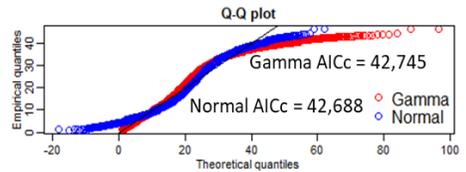
APPENDIX II



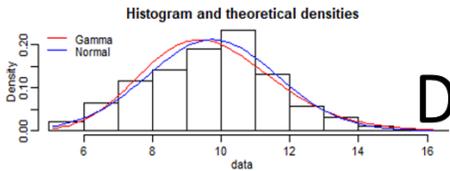
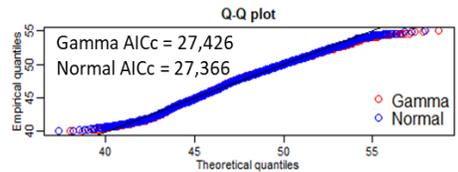
A



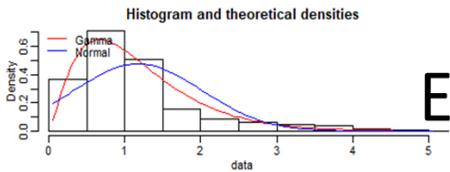
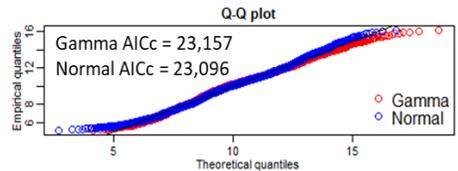
B



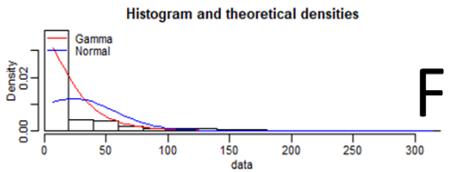
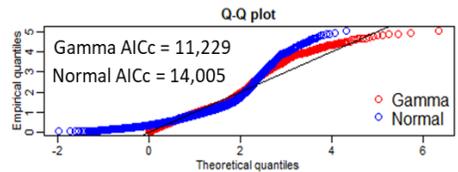
C



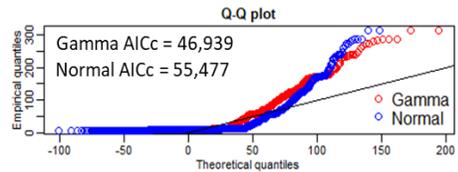
D



E



F



RESEARCH NOTE

## Ecology of Northwestern Pond Turtles in a Sierran Foothill Population, California

DAVID J. GERMANO<sup>1\*</sup>

<sup>1</sup> *Department of Biology, California State University, Bakersfield, CA 93311, USA*

*\*Corresponding Author: dgermano@csub.edu*

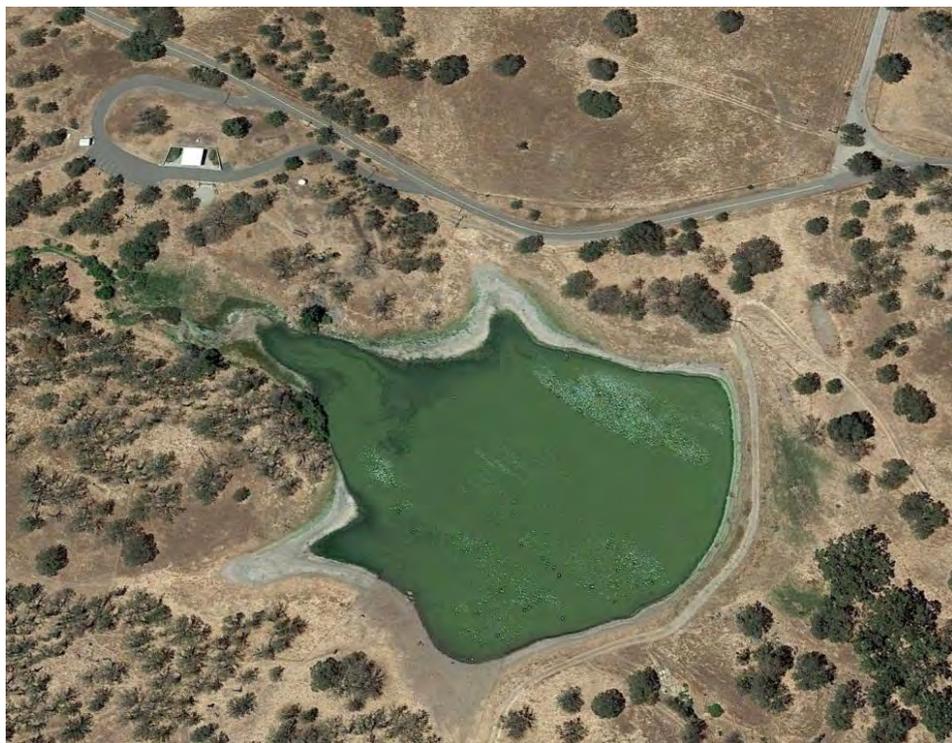
**Key words:** age, California, carapace lengths, clutch size, growth rates, reproduction, weight

---

A species with a broad geographic range can occur in various habitats and elevations, which can affect life-history traits such as individual growth rates and adult body sizes. In turn, these factors can influence survivorship and reproductive success (Schaffer 1974; Stearns 1992; Charlesworth 1994). Colleagues and I have studied populations of western pond turtles (*Actinemys marmorata; sensu lato*) across their range, including natural and artificial ponds, streams, rivers, and reservoirs in Oregon and northern California (Germano and Bury 2009; Bury et al. 2010), as well as in the Central Valley of California (Germano and Bury 2001; Germano 2010, 2016). Further, we studied turtles in natural ponds in coastal California (Germano and Rathbun 2008) and in the Tehachapi Mountains of Southern California (Germano and Riedle 2015). At most sites, we recorded population attributes and life-history traits to broaden the understanding of variability that this species displays along its long latitudinal range (Bury and Germano 2008; Bury et al. 2012). Here, I report on a new site in the foothills of the Sierra Nevada in the central part of the San Joaquin Valley of California, near the southern end of the range of the northwestern pond turtle (*A. marmorata; sensu stricto*).

Starting in 2017, I set traps at the approximately 1.7-ha pond on the Circle J-Norris Ranch (CJNR; Figure 1), east of Porterville, Fresno County, California. The ranch is a 251-ha site in the Sierra foothills now used for environmental education (Tulare County Office of Education. 2020. Circle J-Norris Ranch. Tulare County Office of Education. Available at <http://www.tcoe.org/circlej/> [Accessed 9 June 2020]). The pond is at an elevation of 598 m and the surrounding habitat is an Oak Woodland with non-native grasses as the predominant understory (Figure 1). There was much algal growth and hornwort (*Ceratophyllum demersum*) in the water from the edge of the bank to about 7–8 m when I trapped this site. Algal growth was lower in April and early May but became thicker and spread out farther from shore as temperatures increased in May and June.

I captured turtles from 2017–2019 using both commercial nylon net traps with double funnels (model FTC-FTD; Memphis Net & Twine Company, Inc., Memphis, Tennessee) and homemade chicken wire-mesh traps with double funnels (modified from Iverson 1979). I baited traps with canned sardines, chicken, chicken livers, or commercial fish bait and I



**Figure 1.** Satellite image of the pond (cattle tank) on the Circle J - Norris Ranch educational site, east of Porterville, California. The image was taken in 2016 after several years of drought and the water level was higher in the pond the years I trapped for turtles, 2017–2019. The educational facility is the white square in the upper left of the image. (Image taken from: Google Earth 2020).

left traps open for 3–4 days. I checked traps once daily, usually starting at 0900. I measured turtles on site and released turtles back into the pond after processing. I trapped the site three times in 2017 using 7 traps each session (17–20 May, 5–9 June, and 3–7 July), twice in 2018 using 8 traps (21–25 May) and 7 traps (18–22 June), and twice in 2019 using 8 traps (15–19 April) and 6 traps (13–17 May).

For each captured turtle, I recorded carapace length (CL) to 1 mm, weight to 1 g, sex, and age following Germano (2010). Turtles at this site grow fairly rapidly and discernible scute rings become hard to detect at 12–15 y. I classified some turtles when first captured as older than 15 y when rings were still fairly distinct but the edges of scutes along the midline of the plastron were beveled and > 20 y when plastron rings were well worn and the midline beveled. I defined turtles as adults if they were 120 mm CL or larger, and I individually marked turtles by notching marginal scutes with a file (Cagle 1939; Bury and Germano 1998). To determine if females were gravid and how many eggs were present in a clutch, I radiographed female turtles on site using a portable X-ray machine (HF8020, Minxray, Inc., Northbrook, Illinois).

I tested for differences from a 1:1 sex ratio using Chi-square analyses with Yates correction for continuity. I estimated population size using the Schnabel estimator with the

number of individual turtles caught in 2017 as the initial number marked. Because CL data were normally distributed and homoscedastic, I compared the mean CL between the sexes using ANOVA. To minimize the effect of age structure on size estimates (Case 1976), I also determined the upper quartile CL (UQCL) of adult turtles. Despite small samples sizes, these data were also normally distributed and homoscedastic, and I compared mean UQCL between sexes using ANOVA. I compared mean weights between sexes with ANCOVA with CL as the covariate, excluding weights of females that were gravid. For all test,  $\alpha = 0.05$ .

To determine growth rates of turtles, I fitted age and CL data to the Richards growth model (Richards 1959). This growth model estimates three parameters using CL and age data in the general formula to solve for CL at various ages:

$$CL = \text{asymptotic size} (1 + (M - 1) e^{-(K * (Age - I)) / (1 - M)})$$

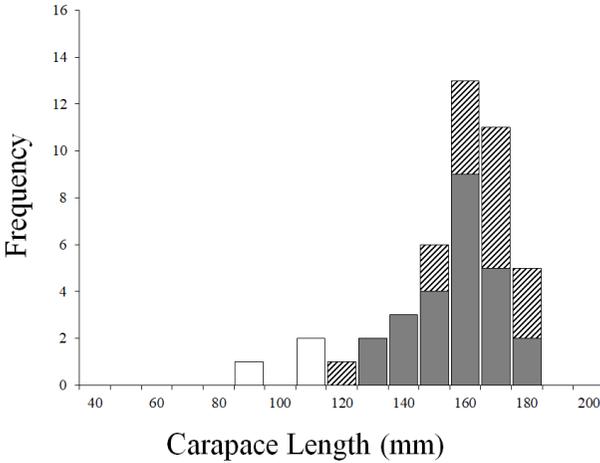
where M is the shape of the growth curve, K is the growth constant, and I is the point at which curve inflection begins. To improve the fit of the curve, I used continuous age estimates (Lindeman 1997) based on a yearly period of 1 May to 30 September that could support growth. I set hatchling size to be 25–29 mm CL based on field data of recent hatchlings (Storer 1930; Feldman 1982; Lovich and Meyer 2002; Germano 2016) to anchor growth curves. To determine a parameter of growth that would allow comparisons with other populations, I used the statistic G, which represents the time required to grow from 10–90% of asymptotic size and is an indicator of the duration of primary growth (Bradley et al. 1984):

$$G = \ln((1 - .10^{1-M}) / (1 - .90^{1-M})) / K$$

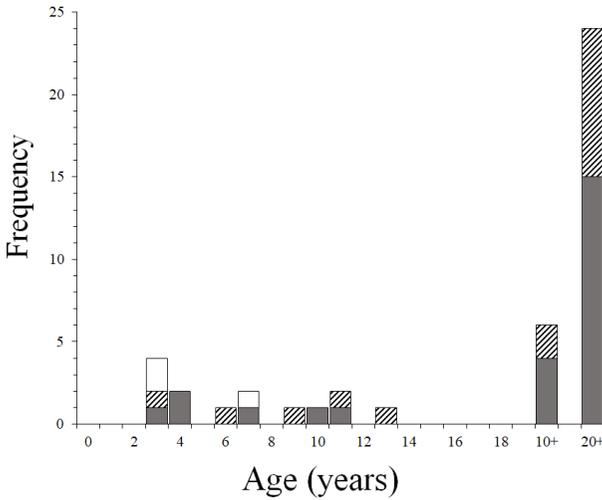
The best overall growth measure is G rather than raw parameters because it is less affected by instability of the non-linear fit than either K or M, and it produces values on an easily interpreted scale (Bradley et al. 1984); in this case, years.

In 2017, I trapped for turtles for 21 trap days (TD) in May, 28 TD in June, and 28 TD in July, resulting in 31 captures of 25 individual turtles. Trap success in 2017 was 0.46 turtles per trap (36 captures/77 TD). In 2018, I trapped for 32 TD in May and 28 TD in June, and in 2019, I trapped for 32 TD in April and 24 TD in May. In 2018, I only made nine captures of eight individuals (five were new) for a trap success of 0.15 turtles per trap (9 captures/60 TD). In 2019, I made 38 captures of 29 individuals (13 were new and not caught in the previous 2 y) for a trap success of 0.67 turtles per trap (38 captures/56 TD). The population estimate of northwestern pond turtles for the 3 y of trapping was 76.2 turtles (95% confidence interval, 52.2–140.7 turtles). Also, in 2017, I caught one female red-eared slider (*Trachemys scripta elegans*) that had a CL of 252 mm and weighed 2,389 g, and another female in 2019 with a CL of 252 mm weighing 2,535 g, which I removed from the site. I also caught non-native catfish (Ictaluridae), sunfish (Centrarchidae), and American bullfrogs (*Lithobates catesbeianus*) each year.

Over the 3-y study, I caught 43 individual northwestern pond turtles: three juveniles (< 120 mm CL), 25 males, and 16 females (Figure 2). One juvenile I caught in 2017 was a male when I recaptured in 2019. Most of the northwestern pond turtles were large, with 76.7% (33 of 43) in the 150 to 180 mm CL categories, and I could determine the age of 32.6% (ages 1–13 y) of the turtles (Figure 2). Of the 43 individuals, 67.4% were older turtles for which I could not determine their age (Figure 2).



**Figure 2.** Distribution of carapace lengths (mm) and ages (years) of northwestern pond turtles (*Actinemys marmorata*) at the Circle J - Norris Ranch educational site, California, 2017–2019. The data are individuals, and if an individual was recaptured, the largest carapace length was used. Juveniles are open bars, males are striped bars, and females are solid bars.



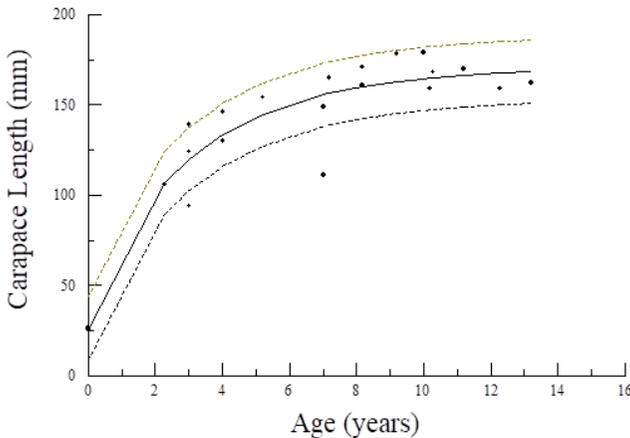
The adult sex ratio (25M:16F) was not significantly different from 1:1 ( $\chi^2 = 1.561$ ,  $df = 1$ ,  $P = 0.212$ ). Although CLs of a few females were larger than any males (Table 1), mean CLs did not differ significantly ( $F_{1,39} = 1.398$ ,  $P = 0.246$ ), nor did the mean upper quartile CLs ( $F_{1,9} = 0.407$ ,  $P = 0.541$ ). I found significant regressions of weight to CL for both males ( $F_{1,23} = 205.0$ ,  $P < 0.001$ ) and females ( $F_{1,9} = 83.10$ ,  $P < 0.001$ ) and mean weights were significantly different ( $F_{1,32} = 2.695$ ,  $P = 0.110$ ).

The mean clutch size of six gravid females was 7.3 +/- 0.494 SE eggs (range, 6–9). In 2017, I found females with eggs as early as 18 May and as late as 5 July. None of the five females I trapped 16–19 April 2019 were gravid, nor were two females on 14 and 17 May 2019. The smallest female with eggs was 145 mm CL and was 20+ y old, and the youngest female with eggs was 10.28 y old and was 168 mm CL in length.

Northwestern pond turtles grew rapidly (Figure 3). Using the growth equation, turtles reached 120 mm CL (small adult) by 3.00 y and 150 mm CL by 5.97 y. The time to grow from 10–90% of asymptotic size (statistic G) was 6.76 y (Table 2).

**Table 1.** Mean (range), sample size (n), and standard error (SE) of carapace length (CL) and weight, and mean upper-quartile CL (UQCL) and weight (UQW) of adult northwestern pond turtles (*Actinemys marmorata*) captured 2017–2019 at Circle J - Norris Ranch in Fresno County, California. Weights of females excludes those that were gravid. The asterisk (\*) is for upper decile parameters.

	CL (mm)				Weight (g)			
	n	Mean (range)	SE	UQCL	n	Mean (range)	SE	UQW
Males	25	157.3 (130–172)	2.75	174.2	25	539.2 (314–767)	24.1	681.8
Females	16	162.5 (124–178)	3.28	175.5	11	675.1 (318–886)	43.1	829.0
Adults	41	159.3 (124–178)	2.14	178.0*	36	580.8 (314–886)	23.7	813.5*



**Figure 3.** Richards growth curve of northwestern pond turtles (*Actinemys marmorata*) from the Circle J - Norris Ranch site in the foothills of the Sierra Nevada in Fresno County, California. The dashed lines are the 95% confidence interval.

I was somewhat limited in the amount of data at this study site because of low trapping success (average trap success for 3 y was 0.40 turtles per trap), especially after the first trapping session of each year. Unlike other sites I have worked at, there was much algal growth and hornwort in the water from the edge of the bank to about 7–8 m out. It may have been hard for turtles to find their way into traps, although I had the best trapping success the first day of trapping in the early months. I tried a variety of baits, but none increased trap success. In 2019, I may have had better success in April (n = 31) and in May (n = 7) because the temperatures were fairly cold and not much aquatic vegetation blocked the traps. Besides red-eared sliders, this site also had non-native catfish (Ictaluridae), sunfish (Centrarchidae), and American bullfrogs (*Lithobates catesbeianus*). The effect of these non-native species have on populations of northwestern pond turtles is uncertain and has not been tested, but it does not seem likely that their presence would have affected the diminishing rate of capture of turtles that I found after initial trapping (day or session). The site would be better for the native northwestern pond turtles, however, if these non-native species were removed.

**Table 2.** Growth parameters from Richards growth curves and the upper decile carapace length (UDCL) for northwestern pond turtles (*Actinemys marmorata*) from three foothill sites and one valley floor site in California. Turtles at the Gorman site now are considered Southwestern Pond Turtles (*A. pallida*). Parameters describing model fit and growth curves from the Richards growth model are shape of curve (M), growth constant (K), inflection point of curve (I), and time required to grow from 10–90% of asymptotic size (G) in years.

Site	M	K	I	G (y)	UDCL (mm)	Reference
Circle J - Norris	-0.4121	0.2869	-1.459	6.76	178.0	This study
Gorman pond	0.0799	0.2415	-0.5625	9.33	171.2	Germano and Riedle 2015
Hell-to-Find Lake	-0.3629	0.1150	-3.528	17.1	166.4	Bury et al. 2010
Fresno Wastewater Treatment Plant	0.0468	0.5582	-0.2355	4.00	181.7	Germano 2010

Turtles at this site are similar in body size and clutch size to those in other parts of its range from the San Joaquin Valley north (Bury and Germano 2008; Germano and Bury 2009; Bury et al. 2010; Germano 2010, 2016). The mean clutch size (7.3 eggs) is larger, however, than those found in turtles in the southern part of the range, which are now considered to be a separate species, the southwestern pond turtle (*A. pallida*). Mean clutch size was 6.3 eggs at Gorman pond, approximately 160 km south of this site (Germano and Riedle 2015), 5.7 eggs at coastal streams in Central California (Scott et al. 2008), and 5.2 eggs at Vandenberg Air Force Base (Germano and Rathbun 2008).

Growth rate (as defined by the statistic G) at this site was higher than for turtles at Gorman pond, south of CJNR, and much higher than for turtles at Hell-To-Find Lake in northern California (Table 2), both of which are foothill to mountain ponds. In these three cases, elevation seems to affect growth rates: CJNR is at 598 m, Gorman pond is at 1,063 m (Germano and Riedle 2015), and Hell-To-Find Lake is at 1,460 m and in a conifer forest (Bury et al. 2010). The growth rate at the study site is slower, however, than at the Fresno Wastewater Treatment Plant (Table 2), which is about 110 km northwest of the ranch but on the valley floor (76 m elevation). Northwestern pond turtles at the Fresno site grow at the fastest rate in the range of this species (Germano 2016).

The pond at CJNR is one of hundreds, if not thousands, of artificial water catchments that have provided habitat for northwestern pond turtles in the past century and a half throughout the species range (Bury and Germano 2008). These sites likely have offset much of the loss of native habitats on valley floors within the range of the species (Bury and Germano 2008). Continued severe drought periods predicted with climate change could be harmful to some population of northwestern pond turtles in these catchments established to water cattle. The recent 2012–2016 drought across California did not cause the pond at CJNR to dry completely, however (Nancy Bruce, personal communication). It will be important to monitor known sites with northwestern pond turtles to determine the effect of continued drought as well as climate change on this species.

## ACKNOWLEDGMENTS

I thank Nancy Bruce, Lead Teacher at the Circle J - Norris Ranch field facility, for allowing me to work at the site. I also thank Bruce Bury for reviewing a draft of this paper. This work was done under permit #SC-955 of the California Department of Fish and Wildlife.

## LITERATURE CITED

- Bradley, D. W., R. E. Landry, and C. T. Collins. 1984. The use of jackknife confidence intervals with the Richards curve for describing avian growth patterns. *Bulletin of the Southern California Academy of Sciences* 83:133–147.
- Bury, R. B., and D. J. Germano. 1998. Annual deposition of scute rings in the western pond turtle, *Clemmys marmorata*. *Chelonian Conservation and Biology* 3:108–109.
- Bury, R. B., and D. J. Germano. 2008. *Actinemys marmorata* (Baird and Girard, 1852) - Western Pond Turtle, Pacific Pond Turtle. Pages 001.1–001.9 in A. G. J. Rhodin, P. C. H. Pritchard, P. P. van Dijk, R. A. Saumure, K. A. Buhmann, and J. B. Iverson, editors. *Conservation Biology of Freshwater Turtles and Tortoises: A Compilation Project of the IUCN/SSC Tortoise and Freshwater Turtle Specialist Group*. Chelonian Research Monographs No.5. IUCN, Gland, Switzerland.
- Bury, R. B., D. T. Ashton, H. H. Welsh, Jr., D. A. Reese, and D. J. Germano. 2012. Synopsis of biology. Pages 9–19 in R. B. Bury, H. H. Welsh, Jr., D. J. Germano, and D. T. Ashton, editors. *Western Pond Turtle: Biology, Sampling Techniques, Inventory and Monitoring, Conservation, and Management*. Northwest Fauna No. 7. The Society for Northwestern Vertebrate Biology, Olympia, WA, USA.
- Bury, R. B., D. J. Germano, and G. W. Bury. 2010. Population structure and growth of the turtle *Actinemys marmorata* from the Klamath-Siskiyou ecoregion: age, not size, matters. *Copeia* 2010:443–451.
- Cagle, F. R. 1939. A system for marking turtles for future identification. *Copeia* 1939:170–173.
- Case, T. J. 1976. Body size differences between populations of the chuckwalla, *Sauromalus obesus*. *Ecology* 57:313–323.
- Charlesworth, B. 1994. *Evolution in Age-structured Populations*. Cambridge University Press, Cambridge, UK.
- Feldman, M. 1982. Notes on reproduction in *Clemmys marmorata*. *Herpetological Review* 13:10–11.
- Germano, D. J. 2010. Ecology of the western pond turtle (*Actinemys marmorata*) at sewage-treatment facilities in the San Joaquin Valley, California. *Southwestern Naturalist* 55:89–97.
- Germano, D. J. 2016. The ecology of a robust population of *Actinemys marmorata* in the San Joaquin Desert of California. *Copeia* 104:663–676.
- Germano, D. J., and R. B. Bury. 2001. Western pond turtles (*Clemmys marmorata*) in the Central Valley of California: status and population structure. *Transactions of the Western Section of The Wildlife Society* 37:22–36.
- Germano, D. J., and R. B. Bury. 2009. Variation in body size, growth, and population structure of *Actinemys marmorata* from lentic and lotic habitats in southern Oregon. *Journal of Herpetology* 43:510–520.
- Germano, D. J., and G. B. Rathbun. 2008. Growth, population structure, and reproduction of the western pond turtle (*Actinemys marmorata*) on the central coast of California. *Chelonian Conservation and Biology* 7:188–194.
- Germano, D. J., and J. D. Riedle. 2015. Population structure, growth, survivorship, and reproduction of *Actinemys marmorata* from a high elevation site in the Tehachapi Mountains of Southern California. *Herpetologica* 71:102–109.
- Iverson, J. B. 1979. Another inexpensive turtle trap. *Herpetological Review* 10:55.

- Lindeman, P. V. 1997. Contribution toward improvement of model fit in nonlinear regression modelling of turtle growth. *Herpetologica* 53:179-191.
- Lovich, J., and K. Meyer. 2002. The western pond turtle (*Clemmys marmorata*) in the Mojave River, California, U.S.A.: highly adapted survivor or tenuous relict? *Journal of Zoology, London* 256:537–545.
- Richards, F. J. 1959. A flexible growth function for empirical use. *Journal of Experimental Botany* 10:290–300.
- Schaffer, W. M. 1974. Selection for optimal life histories: the effects of age structure. *Ecology* 55:291–303.
- Scott, N. J., G. B. Rathbun, T. J. Murphey, and M. B. Harker. 2008. Reproduction of Pacific pond turtles (*Actinemys marmorata*) in coastal streams of central California. *Herpetological Conservation and Biology* 3:143–148.
- Stearns, S. C. 1992. *The Evolution of Life Histories*. Oxford University Press, Oxford, UK.
- Storer, T. I. 1930. Notes on the range and life-history of the Pacific fresh-water turtle, *Clemmys marmorata*. *University of California Publications in Zoology* 32:429–441.

*Submitted: 23 June 2020*

*Accepted: 13 October 2020*

*Associate Editor was A. Baker*

RESEARCH NOTE

## Green Sturgeon (*Acipenser medirostris*) in the San Joaquin River, California: new record

SHAUN T. ROOT<sup>1</sup>\*, ZACHARY SUTPHIN<sup>1</sup>, AND TOWNS BURGESS<sup>2</sup>

<sup>1</sup>Bureau of Reclamation, Fisheries and Wildlife Resources Group, P.O. Box 25007, Denver, CO 80225, USA

<sup>2</sup>Bureau of Reclamation, San Joaquin River Restoration Program, 2800 Cottage Way, Room W-1727 Sacramento, CA 95825, USA

\*Corresponding Author: [sroot@usbr.gov](mailto:sroot@usbr.gov)

**Key words:** California, locality record, *Acipenser medirostris*, Green sturgeon, San Joaquin River

---

Green Sturgeon (*Acipenser medirostris*) are an anadromous species, known to occur along the North American Pacific coast and connected estuaries and rivers, from Ensenada, Mexico to the Bering Sea (Moyle 2002; Wydoski and Whitney 2003; Moser et al. 2016). As mature adults, they return to natal freshwater systems every two to four years to spawn (Moser et al. 2016). There are three known spawning populations of Green Sturgeon. The populations in the Klamath River, California, and Rogue River, Oregon, constitute the northern Distinct Population Segment (DPS), and the spawning population in the Sacramento River Basin, California, constitutes the southern DPS (Adams et al. 2006; Moyle 2002; Moser et al. 2016). Green Sturgeon southern DPS were listed as “threatened” in 2006 under the Federal Endangered Species Act, largely due to loss of critical habitat and declining populations (National Marine Fisheries Service 2006).

During fisheries monitoring activities for the San Joaquin River Restoration Program (SJRRP; Bureau of Reclamation, Region 10 California Great Basin) a single Green Sturgeon was captured on the mainstem San Joaquin River (SJR), California, within the boundaries of the SJRRP Restoration Area (from Merced River confluence to Friant Dam) on 11 April 2020 (Figure 1). The individual was incidentally captured in a fyke trap that was targeting salmonids. The fyke trap is constructed of 5.0-cm chain link formed over 6 consecutive 3.0-m hoops (7-m long x 3-m height). The trap contained two throats with the smaller opening of 60-cm. Trapping location was approximately SJR river kilometer (RKM) 190.7, 300 m upstream of the SJR confluence with the Merced River (37.347065, -120.976280) in the vicinity of Hills Ferry, California. We identified the captured individual using commonly accepted external characteristics, including a noticeable olive green patch on the abdomen, a bony plate behind the anal and dorsal fin, and barbels positioned closer to the mouth than



**Figure 1.** Reclamation Fisheries Biologist with a Green Sturgeon captured incidentally while conducting fisheries monitoring in the mainstem San Joaquin River, California, approximately 300 m upstream of the Merced River confluence with the San Joaquin River, Stanislaus County, CA, USA.

snout (Moser et al. 2016). An adult White Sturgeon (*Acipenser transmontanus*) was also captured in the same trap and was opportunistically used for comparison. Green Sturgeon morphometrics were as follows; 1,260 mm fork length, 1,418 mm total length, and girth of 532 mm. We checked the individual with an Innovasea Systems (Boston, MA) VR100 acoustic receiver and a passive integrated transponder (PIT) reader to determine if the individual was previously tagged. No tissue sample was taken, nor was the individual tagged. We released the individual upstream of the trapping location and appeared healthy upon release.

This finding represents the second confirmed record of an adult Green Sturgeon in the San Joaquin River Basin, upstream of Stockton California, as an adult was confirmed in the Stanislaus River in 2017 (Anderson et al. 2018), and the furthest most upstream confirmed record in the SJR (Moyle 2002; Beamesderfer et al. 2004). Unconfirmed angler reports (Dubois and Danos 2016) have been discounted, for the purpose of this note, due to potential errors in reported capture locations (Dubois, J. California Fish and Wildlife, personal communication). This record extends Green Sturgeon reported range ~71 RKM, and represents a new record for Stanislaus County, California, USA (Moyle 2002). Though spawning was not observed and has never been reported for the species in the SJR, the date of capture was within the timeframe of reported spawning immigrations of adult Green Sturgeon in the Sacramento River basin (March–June; Benson et al. 2006; Heublein et al. 2009).

## ACKNOWLEDGMENTS

Funding was provided by the San Joaquin River Restoration Program. Special thanks are extended to G. Nelson, and D. Portz, as well as all other Bureau of Reclamation personnel that have made this project possible. We are especially thankful for the reviews of the manuscript provided by external peer reviewers.

Any use of trade, product, website, or firm names in the publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

**Author Contributions**

Conceived and designed the study: ZS, TB

Collected the data: SR

Performed the analysis of the data: ZS, SR

Authored the manuscript: SR, ZS

Provided critical revision of the manuscript: ZS, TB

**LITERATURE CITED**

- Adams, P. B., C. Grimes, J. E. Hightower, S. T. Lindley, M. L. Moser, and M. J. Parsley. 2006. Population status of North American green sturgeon, *Acipenser medirostris*. *Environmental Biology of Fishes* 79:339–356.
- Anderson, J. T., G. Schumer, P. J. Anders, K. Horvath, and J. E. Merz. 2018. Confirmed observation: a North American Green Sturgeon (*Acipenser medirostris*) recorded in the Stanislaus River, California. *Journal of Fish and Wildlife Management* 9(2):624–630.
- Beamesderfer, R., M. Simpson, I. Fuller, and D. Demko. 2004. Historical and current information on green sturgeon occurrence in the Sacramento and San Joaquin Rivers and tributaries. Report by S.P. Cramer & Associates to State Water Contractors, Sacramento CA, USA.
- Benson, R. L., S. Turo, and B. W. McCovey, Jr. 2006. Migration and movement patterns of green sturgeon (*Acipenser medirostris*) in the Klamath and Trinity rivers, California, USA. *Environmental Biology of Fishes* 79:269–279.
- DuBois, J., and A. Danos. 2017. 2016 Sturgeon fishing report card: preliminary data report. Stockton, California: California Department of Fish and Wildlife. Available from: <https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentId=141241&inline>
- Heublein, J., J. Kelly, C. Crocker, P. Klimley, and S. Lindley. 2009. Migration of green sturgeon, *Acipenser medirostris*, in the Sacramento River. *Environmental Biology of Fishes* 84:245–258.
- Moser, M. L., J. A. Israel, M. Neuman, S. T. Lindley, D. L. Erickson, B. W. McCovey, Jr., and A.P. Klimley. 2016. Biology and life history of the Green Sturgeon (*Acipenser medirostris* Ayres, 1954): state of the science. *Journal of Applied Ichthyology* 32(S1):67–86.
- Moyle, P. B. 2002. *Inland Fishes of California*. Revised and expanded. University of California Press, Berkeley, CA, USA.
- National Marine Fisheries Service (NMFS). 2006. Endangered and threatened wildlife and plants: threatened status for southern distinct population segment of North American Green Sturgeon; Final Rule. *Federal Register* 71(67):17757–17766.
- Wydoski, R. S., and R. R. Whitney. 2003. *Inland Fishes of Washington*, revised and expanded. 2nd edition. University of Washington Press, Seattle, WA, USA.

*Submitted: 14 July 2020*

*Accepted: 17 August 2020*

*Associate Editor was P. Reilly*

## BOOK REVIEW

### **Ruling the Waters: California's Kern River, the Environment, and the Making of Western Water Law**

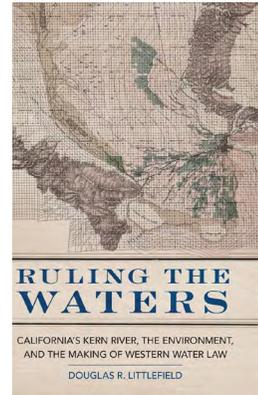
Douglas R. Littlefield. 2020. *The Environment in Modern North America*; Volume 4. University of Oklahoma Press, Norman, OK, USA. 278 pages (hard cover). \$45.00. ISBN: 978-0806164908

While you are most likely to find this book on a college syllabus, it does not necessarily read like a traditional piece of academic literature. This relatively short, but dense book is packed with facts and figures depicting how the development of the San Joaquin Valley influenced California water law. Specifically, how the water law of prior appropriation now legally exists simultaneously with the doctrine of riparian water rights in California.

The narrative takes on a story-like quality using clippings from newspapers such as *Bakersfield California*, the *Mountain Democrat*, and the *San Francisco Chronicle*, along with excerpts from journals and historical records. By using firsthand accounts, Littlefield takes you on a journey of land 'reclamation' and acquisition to water management and ownership, describing the people, politics, and conflicts along the way. While the book provides the historical backdrop and political circumstances for the entire San Joaquin Valley during the eighteenth and nineteenth century, Littlefield largely focuses on the development of the Kern River watershed. This is because of the substantial number and importance of the lawsuits and resulting legislation derived in Kern County.

Central to the book, is Littlefield's explanation of the importance of the 1886 *Lux v Haggin* water rights ruling involving the Kern River, discussing how the acceptance of riparian rights by the California Supreme Court endorsed a concept of private property that included water as a usufruct. Further, he describes why the recognition of riparianism was not favored by all and explains how the ruling set the stage for water disputes to proliferate throughout the state and the west in general. Reading through the various legal challenges, I can't help but wonder what water management, in California, might look like today had courts only recognize appropriation, as many other states did when establishing their own water law.

Though this book touches on many issues that fundamentally shaped water management in California, such as the gold rush and hydraulic mining, the displacement of Native Americans, resulting influences of the Civil War, and large infrastructure development, it really centers on the people and conflicts directly connected to the creation of the California Doctrine. Each chapter takes on an important milestone in the development of the Kern River watershed and California water law. Littlefield starts by describing the original motivation behind draining the San Joaquin Valley as the desire for increased navigable water transportation coupled with a strong public opinion that by draining the swamps, the water could be used "to suit the interests of agriculture, watering a large portion of the valley, and making



it a garden" (p.17). As time passes and legislation evolves there are many failed attempts to drain the San Joaquin Valley, causing the legislative focus to shift from transportation necessity to settlement, reliable water supply, and for some, profit.

While each chapter generally tackles a new development in the efforts towards converting the San Joaquin Valley from marshlands to managed agriculture, many conflicts and resulting legal challenges transpire. These issues were complex, and many remain to this day. As such, several of the key court cases and decisions presented, such as the California Supreme Court decision *Lux v. Haggin* and the 1888 Miller-Hagger Agreement, are discussed and referenced in multiple chapters. While this makes sense, it can lead to a bit of repetitiveness when following along in the book and sometimes confusion, as the storyline might jump forward in time or revisit the past to provide more context and detail to a focal point of a chapter.

An interesting facet of the book is the biographical examination of many influential people involved in altering the San Joaquin Valley. Take Thomas Baker, the namesake of Bakersfield, Littlefield not only describes how Baker led reclamation efforts in the Central Valley but also describes him through historical account as someone who sympathized with the south during the Civil War resulting in his arrest for sedition. After a short stint at Alcatraz and a few years of legal headache, Baker was acquitted of treason but nonetheless directly delayed reclamation efforts in the San Joaquin Valley. Much of the book is spent portraying influential figures such as Baker, Henry Miller, and Charles Lux and it helps humanize the story of water law in California. By understanding the personal and political gains of these individuals, we begin to understand the influences that helped to create the complex system of water management and law we operate under today.

In addition to detailing the progression of California water law, Littlefield provides commentary throughout the book on the environment. However, the discussion presented is mostly an acknowledgement that the environmental impacts were simply not considered at the time. Littlefield does try and describe the extent of impact, loss of species and species diversity, and overall transformation of the San Joaquin Valley from that of the largest wetlands in the western United States to the arid agricultural fields dominating the landscape today. The vivid descriptions and maps provided of the historical Central Valley landscape are thought provoking. They led me to evaluate the objectives and goals of present-day environmental efforts. Currently, environmental permits and plans are often designed to mitigate for further loss of species and habitat, and/or restore landscapes to function at a level depictive of Littlefield's post nineteenth century development. I wonder, should we be doing more to address the environmental impacts caused by water supply development in the past or have we resigned ourselves to simply maintaining the fundamentally decreased functionality of habitats present?

In discussing how various portions of the San Joaquin Valley went from wetlands with too much water to arid agricultural lands with too little or unreliable water supplies, Littlefield observes the development of levees, drainage ditches, reservoirs, and conveyance canals. However, the book does not focus on the construction or engineering feats associated with altering the landscape. Rather, it examines the evolution of land use through first the policy guiding water infrastructure development resulting in increased water supply reliability, then increased settlement and dependence on water supply. Subsequently, Littlefield uses this narrative to provide context to the ensuing conflict over water sources and ownership, ultimately leading to litigation and law.

As I read through the book, I realized that not only was the reclamation of the San Joaquin Valley a testament to water development but that many of the strategies used to settle water disputes historically are still used today. For example, Littlefield writes that the 1888 Miller-Hagger Agreement demonstrated the desire for westerners to compromise, to keep water issues decentralized and with local and regional control. Current endeavors such as the State Water Resources Control Board efforts to update the San Joaquin Water Quality Control Plan have subsequently led to the development of the Voluntary Agreements. Although still under negotiation, the political pressure for the pursuit of Voluntary Agreements demonstrates the same desire by water users to compromise in order to dissuade the state from interfering with local water management.

In summary, Littlefield does a great job of making water case law interesting and comprehensible to those of us with limited legal understanding. *Ruling the Waters* provides an insightful account of the people, politics, and court proceedings largely responsible for the legislation and subsequent management of water resources in California today. Overall, this book successfully makes the case that understanding the evolution of the Kern River watershed is important to the historical understanding of American water law.

PAIGE UTTLEY, *Senior Environmental Scientist (Supervisor), Water Branch, California Department of Fish and Wildlife, 1010 Riverside Parkway, West Sacramento, CA 95605, USA*

## BOOK REVIEW

# The Cougar Conundrum: Sharing the World with a Successful Predator

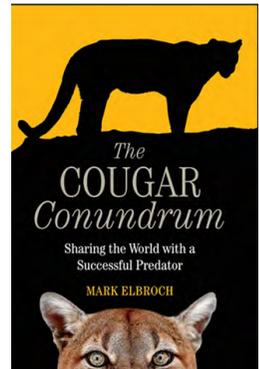
Mark Elbroch. 2020. Island Press, Washington, DC, USA. 250 pages (soft cover). \$30.00. ISBN:9781-61091-998-2

**cougar:** a large, powerful tawny brown cat (*Felis concolor*) (Gove 1971)

**conundrum:** (1) a question or problem having only a conjectural answer; (2) an intricate and difficult problem (Gove 1971)

Dr. Mark Elbroch is well-known as the author of several natural history books, the majority of which are useful field guides. He also is an accomplished scientist, and has become a prolific contributor to the scientific literature on mountain lions, a species to which he refers as cougar—or mountain lion—throughout this book. I very much appreciate that because those names are in common use throughout the United States and Canada, and I find the increasingly frequent use of puma to be couched more in ‘political correctness’ or novelty than are cougar or mountain lion.

With publication of *The Cougar Conundrum*, Mark Elbroch has written about an intriguing topic that will be of some interest. The author clearly holds cougars in high regard and is knowledgeable about their ecology. He has been on the cutting edge of the application of new technologies that have provided insights into the ‘private lives’ of these cryptic felids, but he also has emphasized the value of traditional field work (Elbroch et al. 2018), an important point evidenced further by his statement (p. 21) that, “Most North American researchers spend their entire careers trying to learn something about mountain lions from the blips and bleeps of handheld receivers [or locations displayed on a computer screen], rather than from any opportunity to actually observe the animals...”. It also is clear that he considers mountain lions to be incredibly special animals, and a theme I detected throughout the book is that they warrant incredibly special consideration. For example, in the preface Elbroch describes the potential demise of a small population of mountain lions occupying the Santa Monica Mountains, an insular bit of habitat about 710 km<sup>2</sup> (275 mi<sup>2</sup>) in area, and writes (p. xvii) that, “[R]esearchers and wildlife advocates work to save a mountain lion population that, just 60 years previously, was *likely extirpated* [emphasis added] following state-paid bounties for dead mountain lions [in California].” No evidence is provided to substantiate that statement and, given the low effective sizes of mountain lion populations proximate to the Santa Monica Mountains (Gustafson et al. 2019), it is unclear from whence the founders of the current ‘population’ would have originated. Although not stated explicitly, Elbroch



appears to believe that the policies, regulations, and legislation currently in play in California represent an ideal model for mountain lion management and conservation throughout North America. I would argue strongly that such is not the case.

*The Cougar Conundrum* consists of 10 chapters, each dedicated to a separate, albeit general, theme. In Chapter 1, the author summarizes, and then debunks, a number of misconceptions about mountain lions, and Chapter 2 is dedicated to staying safe in mountain lion habitat. In Chapter 2, Elbroch parrots many recommendations previously put forth by others, but also emphasizes that mountain lions are timid, and more likely to flee than to attack. He notes (p. 32), “It’s a dangerous world out there, but mountain lions pose little risk when compared to all the other dangers.” In Chapter 3 (Of Lions, Pets, and Livestock) the author posits that, “Mountain lions are intelligent carnivores, quick to seize opportunities for an easy meal” (p. 58), a statement in which I found a bit of irony given the aforementioned reference to little risk, and the emphasis on behavioral differences among individual cougars that occurs throughout the book. The remainder of the chapter goes on to present examples of, examine problems associated with, and suggest potential solutions to predation on livestock and pets.

While reading Chapter 4 (Sharing Prey with Mountain Lions), I became much more interested in the book. Therein, he explores cougar predation, prey availability, hunter harvest, and competition for native ungulates between mountain lions and humans. Elbroch emphasizes (p. 90) that the restoration of desert bighorn sheep to historical ranges in New Mexico occurred because the chief advocate for doing so was, “[s]tubbornly set on increasing bighorn sheep numbers *to where they could be harvested by sportsmen again* [emphasis added] ...”, rather than acknowledging that desert bighorn sheep were at risk of extinction in New Mexico, and that recovery and de-listing was consistent with the State’s public trust stewardship of its wildlife resources (Rominger et al. 2006). Further, Elbroch makes no mention of the non-native ungulates, whether livestock, feral equids, or large exotic artiodactyls that likely have played a role in subsidizing resources for mountain lions, and thereby yielding a greater density or wider distribution of cougars than otherwise would have been the case. Shortly thereafter (p. 92), he notes that where deer formerly were absent, but now are sympatric with bighorn sheep, presence of those cervids has contributed to increased predation on bighorn sheep. Mention of feral or exotic ungulates, or free-range domestic livestock, in a similar context would have been appropriate, meaningful, and helpful.

In Chapter 5 (The Great Hunting Debate), Elbroch delves into the topic of cougar hunting, beginning the chapter (p. 99) by describing a recent review that emphasized “rampant trophy hunting” as—by far—the greatest threat to mountain lions in the United States and Canada (HSUS 2017). He then describes a subsequent critique (Cain and Mitchell 2018) prepared by researchers with the USGS Cooperative Research Unit Program (CRUP). An important role of the CRUP is to provide support in the form of objective and independent scientific reviews of ‘gray’ literature—of which the HSUS report is a classic example—but that role is not mentioned. Instead, Elbroch describes the critique as the result of concerns, voiced by “state wildlife agency personnel,” that the HSUS document could undermine current mountain lion management. That statement denigrates the reputations of state and federal agency biologists, and does nothing to enhance conservation of mountain lions. Much of the remainder of the chapter addresses the status of cougars in the context of harvest and its potential impacts to lion populations, but offers neither a defense of the HSUS document nor a rebuttal of Cain and Mitchell (2018).

In Chapter 6 (Lions on the Eastern Seaboard), the author examines evidence in support of and contrary to the persistence of the 'eastern cougar.' Declaration of that extinction in 2018, when combined with the synonymy of virtually all cougars in North America, could simplify a future introduction effort. Chapter 7 (How to Love a Keystone Predator) revived my interest, and it will evoke negative responses from some readers, and accolades from others. As an example, his statement (p. 152) that, "[D]ominionistic hunters driven by money and power wielded by the likes of Safari International [sic] are increasingly damaging hunters' reputations and our natural resources as a whole" followed by, "Dominionistic hunters are unlikely to be interested in the conservation of mountain lions or any wildlife..." Perhaps inclusion of such statements are an effort to stir debate, but I do not see them being helpful in 'big-picture' wildlife conservation.

Throughout the text the author criticizes state wildlife conservation agencies and, in my opinion, greatly disserves those that have dedicated their lives to the conservation of wildlife, whether hunted or not. On page 168, he states emphatically that those agencies "[f]ocused on wildlife management and emphasized the sustainable, wise use of natural resources, whereas the other [i.e., universities and external organizations] focused on understanding, preserving, and restoring biodiversity as a means of ensuring ecosystem health and resilience." That is an overstatement and entirely inappropriate, and further demeans the historical efforts of many, as will be emphasized in the penultimate paragraph of this review.

In Chapter 8, "The Money Behind Mountain Lion Management," Elbroch again expresses a lack of confidence in, and further disdain for, the state agencies charged with wildlife conservation and the dedicated biologists tasked with that public trust responsibility, whom he identifies repeatedly as beholden to special interest groups. No topics seem immune from criticism; among these are several national or international organizations including—by inference (p. 194)—The Wildlife Society (a professional society "[t]hat represents management-minded biologists and their interests..."). Also criticized is landmark legislation that has been very meaningful for conservation, as well as the North American Model of Wildlife Conservation and its primary authors. Elbroch is adamant (p. 194) that the North American Model "[is] our past, but it should not be our future," and emphasizes (p. 195) that, "There are many *wonderful, progressive-minded people working for state agencies* [emphasis added], and we must be careful not to confuse people with the institutions for which they work, or with the political governing bodies that sometimes dictate their priorities and approve their funding." That statement caused me to question what 'progressive-minded people' represent, and just what their presence portends for those agencies.

In the final chapter, "Toward Coexistence with Mountain Lions," Dr. Elbroch lays out his vision for the future of cougars and argues (p. 218), "They are evidence of true wildness, graceful, majestic, and strong." I emphasize, however, that those cryptic felids also are highly adaptable, and are capable of existing as viable populations under a multitude of disparate conditions and stressors where habitat is adequate to maintain a prey base and large enough in size to support more than a few cougars at any given time. Mountain lion populations occurring under such conditions do not require anthropogenic intervention to ensure persistence. Nevertheless, cougars have elevated emotions among the general public to the point of driving conservation and management. Many individuals insist the presence of those large carnivores is essential in isolated areas that are tiny in size and surrounded by urbanization and associated infrastructure, or where they present a risk to human safety. I suggest it is neither desirable nor essential for mountain lions to occupy every square ki-

lometer of 'suitable habitat' within their historical range, especially given the ongoing and highly successful efforts to ensure their persistence across the landscape, and a constantly expanding geographic distribution. Unfortunately for mountain lions—and for the large native herbivores on which they depend—it is not until late in the book (p. 202), that destruction of habitat in the United States and Canada is emphasized adequately in terms of its impacts. I suspect mountain lions would have been better served had the importance of habitat been emphasized from the very beginning and had been a recurring theme throughout the book.

It is not my purpose to demean an attempt to call attention to some serious issues with which society and wildlife are faced, particularly with respect to a controversial topic. In my opinion, however, that effort could have been accomplished more effectively had the author relied on fewer personal opinions and more heavily on the peer-reviewed literature, and had incorporated a greatly expanded list of references. Additionally, I found organization of the book to be confusing and a bit burdensome. It is my impression that the author intended a 'point-counterpoint' approach, but that was not entirely clear. Further, literature used to substantiate statements varied in terms of its source or level of 'quality control', with some originating as online, unrefereed opinions or popular articles, some from highly regarded academic journals, and additional sources that the author refers to as counterfeits and describes (p. 166) as "[p]redatory journals that will publish anything anyone has written and claims to be science." It would have been immensely helpful had citations been included at the end of each chapter, rather than grouped by chapter at the end of the book, because efforts to consult in-text citations were extremely time-consuming.

I was at a disadvantage when preparing this review because I received what was described as "advance reader's edition" and was cautioned against quoting material until it was checked against the final, printed edition. I noted several minor errors in the advance edition that were corrected in the published version; other errors remained, however, and at least one mistake not in the advance edition appeared in the final publication. Among the most egregious errors remaining in the final version centered on the Federal Aid in Wildlife Restoration Act (i.e., the Pittman-Robertson Act), which is referred to at least 6 times as the "Pittman-Roberts Act."

Dr. Elbroch has been described (p. 239) as a "soulless bastard" for enslaving mountain lions for research purposes, and as a "Σ#!†-for-brains" liberal for his views on mountain lion hunting; despite publication of *The Cougar Conundrum*, I suspect those descriptors will remain. Combinations of facts, opinion, emotion, speculation, and criticism—some of which will foment strong reactions—occur throughout the book. Yes, there is a 'cougar conundrum' and it warrants discussion; I found the book itself, however, to be a conundrum that is unlikely to decrease the divisiveness that pervades issues related to the conservation of mountain lions.

Bruce Wilcox and, the late, Michael Soulé are revered as founding fathers of the discipline commonly referred to as Conservation Biology. Some 40 years ago, when penning their ground-breaking work bearing that title, Soulé and Wilcox (1980) emphasized that, "[T]he emergence of conservation biology as a respectable academic discipline has been slowed by prejudice. Until recently, few academically oriented biologists would touch the subject. While wildlife management, forestry, and resource biologists [s]truggled to buffer the most grievous or economically harmful of human impacts (deforestation, soil erosion, overhunting), the large majority of their academic colleagues thought the subject was below their dignity. But academic snobbery is no longer a viable strategy, if it ever was. [T]he

luxury of prejudice against applied science is unaffordable.” Although not acknowledged in *The Cougar Conundrum*, the discipline of Wildlife Management was ahead of the times.

VERNON C. BLEICH, *Department of Natural Resources and Environmental Science, University of Nevada Reno, and Eastern Sierra Center for Applied Population Ecology, Bismarck, ND, USA*

### LITERATURE CITED

- Cain, J. W. III, and M. S. Mitchell. 2018. Evaluation of key scientific issues in the report, “State of the mountain lion—a call to end trophy hunting of America’s lion.” U.S. Geological Survey Open-File Report 2018-1128.
- Elbroch, L. M., B. Lowery, and H. U. Wittmer. 2018. The importance of fieldwork over predictive modeling in quantifying predation events of carnivores marked with GPS technology. *Journal of Mammalogy* 99:223–232.
- Gove, P. B. (editor). 1971. Webster’s seventh new collegiate dictionary. G. & C. Merriam Company, Springfield, MA, USA.
- Gustafson, K. D., R. B. Gagne, T. W. Vickers, S. P. D. Riley, C. C. Wilmers, V. C. Bleich, B. M. Pierce, M. Kenyon, T. L. Drazenovich, J. A. Sikich, W. M. Boyce, and H. B. Ernest. 2019. Genetic source-sink dynamics among naturally structured and anthropogenically fragmented puma populations. *Conservation Genetics* 20:215–227.
- Humane Society of the United States (HSUS). 2017. State of the mountain lion—a call to end trophy hunting of America’s lion. Humane Society of the United States, Washington, D.C., USA.
- Rominger, E. M., V. C. Bleich, and E. J. Goldstein. 2006. Bighorn sheep, mountain lions, and the ethics of conservation. *Conservation Biology* 20:1341.
- Soulé, M. E., and B. A. Wilcox. 1980. Conservation biology: its scope and its challenge. Pages 1–8 in M. E. Soule and B. A. Wilcox, editors. *Conservation biology: an evolutionary-ecological perspective*. Sinauer Associates, Sunderland, MA, USA.

## INFORMATION FOR AUTHORS

The California Fish and Wildlife Journal (CFWJ) is a peer-reviewed, scientific journal focused on the biology, ecology, and conservation of the flora and fauna of California and surrounding areas, and the northeastern Pacific Ocean.

The CFWJ now has an **online submission system!**

New! All manuscripts should now be submitted using the online submission system. **Submissions guidelines (PDF)** for the Journal have been updated (December 2020) to reflect this change.

The California Fish and Wildlife Journal accepts manuscripts in the following categories:

Original research papers

Research notes and short communications

Monographs

Review papers

Book reviews

Essays

Commentaries on previously published papers

Manuscripts must be submitted following directions provided in the **CFWJ Revised Submission Guidelines (December 2020) (PDF)**. Please follow these formatting guidelines carefully. Manuscripts that do not conform to the guidelines will be returned for revision.

The CFWJ uses a double-blind peer review process. This means that reviewer identities are concealed from authors as well as author identities being concealed from reviewers throughout the review process. This policy aids in reducing bias during the review process.

Authors of manuscripts that are accepted for publication will be invoiced for charges at the rate of \$50 per printed page shortly after page proofs are distributed.\* The corresponding author will receive a PDF file of the publication without additional fees and may distribute copies without restriction.

\*Page charges may be waived for authors under in certain instances (e.g., for authors from developing countries, researchers without funding, etc.).

Send any questions to:

Ange Darnell Baker, PhD

Editor-in-Chief, California Fish and Wildlife Journal

California Department of Fish and Wildlife

(916) 376-8671

Angela.Baker@wildlife.ca.gov

## Subject Matter Index for California Fish and Wildlife 106 (2020)

- Acipenser medirostris*, 268
- Acipenser transmontanus*, 59
- age estimation, 205
- age validation, 205
- agriculture, 203
- altitude, 156
- anadromous, 99
- anadromous adults, 39
- Anaxyrus woodhousii*, 258
- artificial perches, 203
- atresia; 7, 215
- Barred Sand Bass; 139, 205
- baseline, 99
- Beach rehabilitation, 11
- black-tailed deer, 170
- Bufo woodhousii*, 258
- Buteo jamaicensis*, 203
- Buteo lineatus*, 203
- bounty, 66
- California; 170, 260, 268
- California condor, 191
- camera traps, 203
- carapace lengths, 260
- Carquinez Strait, 59
- Cascade frog, 215
- Clear Lake, 186
- Clear Lake Hitch, 186
- clutch size, 260
- comparative hematology, 156
- cougar, 156
- crustaceans, 19
- Delta Smelt, 19
- depredation, 66
- dispersal, 258
- Eastern Tehama deer herd, 170
- estuary, 226
- Eucalyptus, 220
- Falco sparverius*, 203
- feeding, 191
- fish, 99
- fish diets, 19
- fisheries resources, 221
- fishery independent assessment, 139
- flow-mediated water temperature, 221
- flow-type, 99
- foraging, 203
- geographic variation, 156
- giant sea bass, 11
- Green sturgeon, 268
- Growth, 205
- growth rates, 260
- hematology, 156
- hydroacoustics, 139
- impacts, 226
- invasive species, 19
- locality record, 268
- Longfin Smelt, 19
- managed flows, 99
- management, 220
- micro-trash, 191
- migration, 170
- migration patterns, 99
- monarch butterfly, 220
- mortality, 66
- mountain lion, 156
- Mysidacea, 19
- native plants, 220
- naturalized species, 226
- non-anadromous, 99
- nursery site, 11
- Odocoileus hemionus columbianus*, 170
- Oocytes; 7, 215
- osteological deformity, 186
- otolith, 205
- overwintering, 220
- Paralabrax nebulifer*; 205
- pests, 203
- pulse flows, 99
- puma, 156
- Puma concolor*; 66, 156
- Rainbow Trout, 39
- Rana cascadae*, 215
- Rana sierrae*, 7
- range expansion, 258

**Subject Matter Index cont.**

raptors, 203  
reference interval, 156  
regulated river, 221  
reproduction, 260  
river, 99  
river restoration, 221  
Rocky Mountain toad, 258  
Rodents, 203  
Sacramento, 19  
salmonids, 226  
Salton Sink, 258  
San Francisco Estuary, 59  
San Joaquin Delta, 19  
San Joaquin River, 268  
SARIMA, 221  
seasonal ranges, 170  
ship strike, 59  
Sierra Nevada yellow-legged frog, 7  
southern California, 39  
Southern Steelhead, 39  
Spawning; 7, 215  
spawning aggregations, 139  
*Stereolepis gigas*, 11  
Spermiogenesis; 7, 215  
stopovers, 170  
Striped Bass; 19, 226  
temperature tolerance, 19  
time series modeling, 221  
Tropical Storm Kathleen, 258  
vehicle strike, 66  
vessel strike, 59  
weight, 260  
White Sturgeon, 59  
Zooplankton, 19

**Author Index for California Fish and Wildlife 106 (2020)**

Allen, L. G.  
Avila, M.  
Baker, A. D.  
Bleich, V. C.  
Bolser, D. G.  
Booth, M. T.  
Boughton, D. A.  
Erisman, B. E.  
Burgess, T.  
Carlino, J.  
Clucas, B.  
Couffer, M. C.  
Dagjt, R.  
Daniel, S.  
Davis, A.  
Dellinger, J. A.  
Demetras, N. J.  
Douglas, L.  
Ernest, H. B.  
Feyrer, F.  
Figura, P. J.  
Germano, D. J.  
Goldberg, S. R.  
Gomez, M.  
Gulak, M. M.  
Hartman, R.  
Helwig, B. A.  
Hileman, J. P.  
Hill, S. C.  
Hovey, T. E.  
Howard, S.  
Jacobson, S.  
Jarvis-Mason, E. T.  
Kanga Livingstone, S. L.  
Kathan, J.  
Kerr, K. J.  
Koehn, K. M.  
Larson, M.  
Lewis, S. D.  
Lloyd, K. A.  
Longcore, T.  
Lopez, S.  
Mccanne, D.  
Mchuron, A. S.  
Medina, J. A.  
Miller, E. A. S.  
Pareti, J. S.  
Penttila, K. M.  
Pierce, B. M.  
Prior, A. M.  
Rich, C.  
Robinson, T. H.  
Root, S. T.  
Sandoval, M.  
Shedlock, A.  
Smith, T. N.  
Sullivan, R. M.  
Sutphin, Z.  
Thornton, S.  
Torres, S. G.  
Valle, C. F.  
Villepique, J. T.  
Walker, K. M.  
Weiss, S. B.  
Won, C.  
Young, M.

**Front.** Northwestern pond turtle (*Actinemys marmorata*). Photo by Dagmar Collins (CC BY-NC-ND 2.0)

**Back.** Barred sand bass (*Paralabrax nebulifer*). Photo by Josh More (CC BY-ND 2.0).



[www.wildlife.ca.gov/science](http://www.wildlife.ca.gov/science)