DWR 1136

UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL MARINE FISHERIES SERVICE
West Coast Region
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Memorandum to: CVP/SWP Operations Opinion
Administrative Record Number 151422SWR2006SA00268

From: Brycen Swart, Fisheries Biologist Brycen Swart

Subject: Shasta Operations Temperature Compliance Memo

Introduction

California has just ended its fourth consecutive year of below-average rainfall and snowpack, resulting in significant adverse effects to juvenile winter-run Chinook salmon populations. Due to a lack of sufficient inflow and cold water pool in Shasta Reservoir and competing water demands in 2014 and 2015, Sacramento River water temperatures rose to sub-lethal and lethal levels contributing to very low egg-to-fry survival of juvenile winter-run Chinook salmon estimated to pass Red Bluff Diversion Dam (RBDD) in brood years 2014 (5.6%) and 2015 (4.2%), well below the 18-year average of 23.6% survival. In addition, egg-to-fry survival of juvenile winter-run Chinook salmon in brood year 2013 was estimated to be 15.1%, approximately 36% below the 18-year average of 23.6% survival (Figure 1). Adults returning in 2016 are largely the progeny from brood year 2013. Using a newly developed temperature-dependent mortality model, NMFS Southwest Fisheries Science Center (SWFSC) found that in 2014 and 2015, temperature dependent mortality alone resulted in a loss of approximately 77% and 85% of the population, respectively (B. Martin, personal communication, February 23, 2016; attachment).

Since winter-run Chinook salmon spawn every three years, there is a need to conservatively manage for protection of the 2016 winter-run cohort given the year class failures observed in the last two years. The U.S. Bureau of Reclamation (Reclamation) typically uses the 2016 February forecast to provide initial allocations. To the extent that the February forecast is used to determine whether the predicted water delivery schedule is likely to leave sufficient water for temperature management to meet Endangered Species Act requirements, NMFS proposes model inputs to the Sacramento River Water Quality Model and adjustments to the temperature criteria to minimize adverse thermal effects to winter-run eggs and alevin.

Thermal Needs for Incubation and Early Fry Development

Water temperatures significantly affect the distribution, health, and survival of native salmonids in the California Central Valley. Since salmonids are ectothermic (cold-blooded), their survival is dependent on external water temperatures and they will experience adverse health effects when exposed to temperatures outside their optimal range. Salmonids have evolved and thrived under the water temperature patterns that historically existed (*i.e.*, prior to significant anthropogenic impacts that altered temperature patterns) in California Central Valley streams and rivers. Although evidence suggests that historical water temperatures exceeded optimal conditions for salmonids at times during the summer months on some rivers, the temperature diversity in these unaltered rivers provided enough cold water during the summer to allow salmonid populations as a whole to thrive [United States Environmental Protection Agency (EPA) 2003].

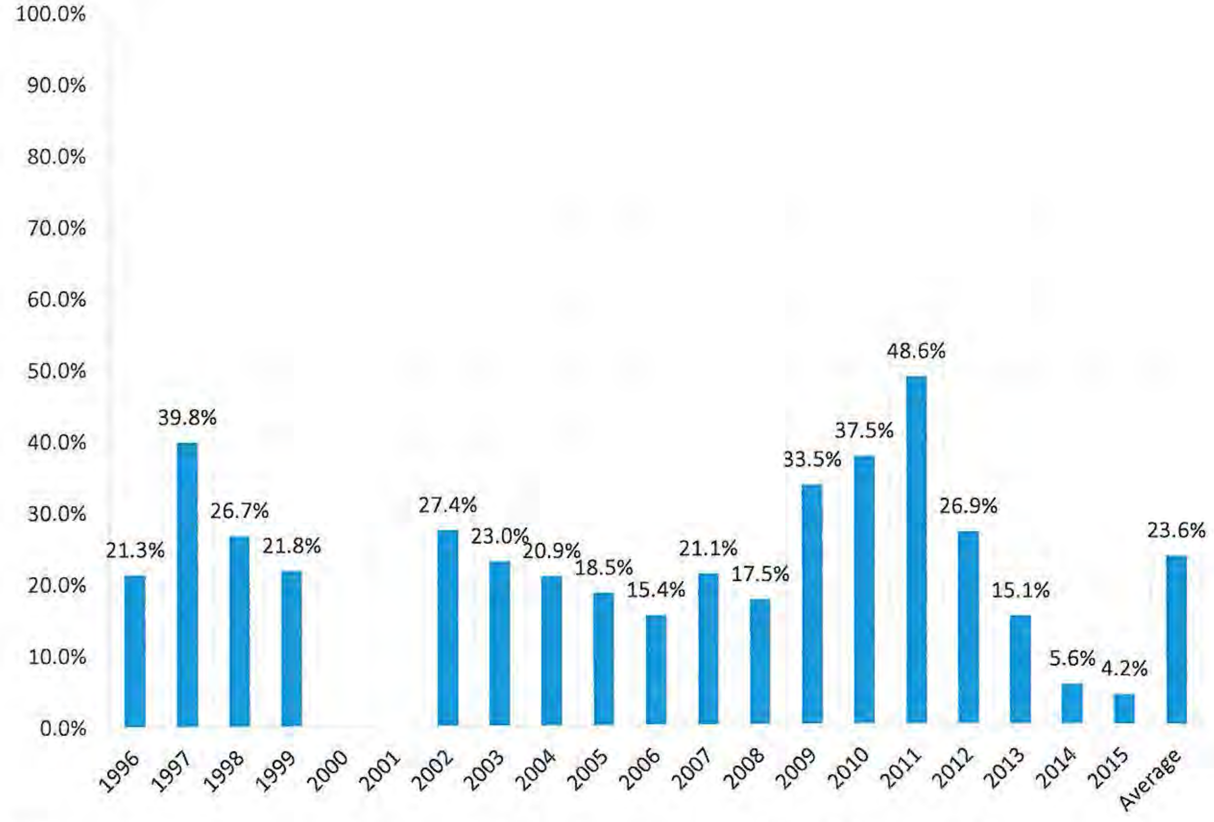

Figure 1. Estimated egg-to-fry survival from passage at Red Bluff Diversion Dam

Pacific salmon populations have historically fluctuated dramatically due to climatic conditions, ocean conditions, and other disturbances. High water temperatures during drought conditions likely affected the historical abundance of salmon. In general, the increased exposure to stressful water temperatures and the reduction of suitable habitat caused by drought conditions reduce the abundance of salmon. Human-caused elevated water temperatures significantly increase the magnitude, duration, and extent of thermal conditions unsuitable for salmonids (EPA 2003).

The effects of water temperature in regulating developmental rates of incubating eggs are well documented (*e.g.*, Hicks 2000, McCullough 1999). During incubation, water temperature affects the rate of embryo and alevin development, the amount of dissolved oxygen in the water, and, to a significant extent, the survival of early fry (Bjornn and Reiser 1991). Within an acceptable range, the higher the temperature is, the faster the rate of development will be, and the shorter the incubation period and time to emergence (Beacham and Murray 1990). Temperatures from 39.2 to 53.6°F (4-12°C) tend to produce relatively high survival to hatching and emergence, with approximately 42.8-50°F (6-10°C) being optimum. Exposure to temperatures above the optimal range results in sub-lethal or chronic effects (*e.g.*, decreased juvenile growth, which results in smaller, more vulnerable fish; increased susceptibility to disease which can lead to mortality; and decreased ability to compete and avoid predation), as temperatures rise until at some point they become lethal.

United States Environmental Protection Agency Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards

Temperature water quality standards are an important tool for the protection and recovery of threatened and endangered salmonid species through maintaining and improving their habitat. In 1999, the EPA Region 10 started a project to develop regional temperature criteria guidance that would be protective of salmonids. States and tribes in the Pacific Northwest could then use this guidance when developing their temperature standards, as required by the Clean Water Act. The criteria guidance was jointly developed by EPA, U.S. Fish and Wildlife Service, National Marine Fisheries Service, States, and Tribes in the Pacific Northwest. They examined the most recent science on how temperature affects salmonid physiology and behavior, the combined effects of temperature and other stressors on threatened fish stocks, the pattern of temperature fluctuations in the natural environment, and other relevant issues. The project culminated in 2003 with the EPA publication of guidance recommendations to States and Tribes on how they can designate uses and establish temperature numeric criteria for waterbodies to protect coldwater salmonid species in the Pacific Northwest.

EPA (2003) recommends a 13°C (55.4°F) maximum 7 day average of the daily maxima (7DADM) criterion for the protection of waterbodies used or potentially used for salmon and trout spawning, egg incubation, and fry emergence and recommends that this use apply from the average date that spawning begins to the average date incubation ends (the first 7DADM is calculated 1 week after the average date that spawning begins). The 7DADM metric is recommended because it describes the maximum temperatures in a stream, but is not overly influenced by the maximum temperature of a single day. Thus, it reflects an average of maximum temperatures that fish are exposed to over a weeklong period. Since this metric is oriented to daily maximum temperatures, it can be used to protect against acute effects, such as lethality, and can also be used to protect against sub-lethal or chronic effects.

EPA (2003) also recommends that water quality standard should apply to all the river miles including the lowest point downstream for egg incubation and fry emergence. Because streams generally warm progressively in the downstream direction, waters upstream of that point will generally need to be cooler in order to ensure that the criterion is met downstream. Thus, a waterbody that meets a criterion at the furthest downstream extent of use will in many cases provide water cooler than the criterion at the upstream extent of the use.

Sacramento River Temperature Compliance Regulatory Requirements

In order to protect salmon egg incubation and fry emergence from adverse thermal effects, the State Water Resources Control Board Orders 90-5 and 91-1 require Reclamation to operate Keswick and Shasta dams to meet a daily average temperature of 56°F at RBDD or at a temperature compliance point (TCP) modified when the objective cannot be met at RBDD based on Reclamation's other operational commitments, including those to water contractors, D-1641 regulations and criteria, and Shasta Reservoir projected end of September (EOS) storage volume.

The 2009 biological and conference opinion on the long-term operation of the Central Valley Project and State Water Project (CVP/SWP operations Opinion) highlights the challenging nature of maintaining an adequate cold water pool in critically dry years, extended dry periods, and under future conditions, which will be affected by increased downstream water demands and climate change. Despite Reclamation's best efforts, severe temperature-related effects cannot be avoided in some years. Reasonable and Prudent Alternative (RPA) Action Suite I.2 includes exception procedures to deal with this reality. Specifically, RPA Action I.2.4 states that Reclamation shall manage Shasta Division operations to achieve a temperature compliance of not in excess of 56°F daily average temperature (DAT) between Balls Ferry and Bend Bridge from May 15 through October 31. In addition, there is a 10-year average performance measure and for temperature compliance points on the Sacramento River during the summer season:

- Meet Clear Creek compliance point 95% of time
- Meet Balls Ferry compliance point 85% of time
- Meet Jelly's Ferry compliance point 40% of time
- Meet Bend Bridge compliance point 15% of time

So far the current 6-year average (2010-2015) since issuance of the CVP/SWP operations Opinion is below this performance metric (see Table 1):

- Clear Creek was met 66% of the time
- Balls Ferry was met 50% of the time
- Jellys Ferry was met 50% of the time
- Bend Bridge was met 0% of the time

Also there is a 10-year average performance measures associated with meeting EOS carryover storage at Shasta Reservoir in order to maintain the potential to meet the various temperature compliance points:

- 87% of years: Minimum EOS storage of 2.2 million acre-feet (MAF)
- 82% of years: Minimum EOS storage of 2.2 MAF and End of April (EOA) storage of 3.8 MAF in following year (to maintain potential to meet Balls Ferry compliance point)
- 40% of years: Minimum EOS storage of 3.2 MAF (to maintain potential to meet Jelly's Ferry compliance point in following year)

The current 6-year average also falls short of this performance metric:

- 50% of Years: Minimum 2.2 MAF
- 50% of Years: Minimum 2.2 MAF and EOA 3.8 MAF
- 33% of Years: Minimum 3.2 MAF

Table 1. Yearly Shasta Reservoir Storages, Water Year Types, Temperature Compliance Points (TCP), Egg-to-Fry Survival, and Various TCP Temperatures.

WY	Beginning of October Storage	End of April Storage	WY Type	TCP	Egg to Fry Survival	SHD DAT	KWK DAT	CCR DAT	CCR 7DADM	BSF DAT	JLF DAT	BND DAT	RBDD DAT
1996	3136	4308	W	BSF	21.3%	51.6	52.3			55.0	55.9	56.0	57.5
1997	3098	3937	W	JLF	39.8%	50.8	51.8			54.5	55.5	56.3	57.1
1998	2308	4061	W	JLF	26.7%	50.7	51.6	52.2	53.3	54.0	55.2	55.4	56.6
1999	3441	4256	W	BND	21.8%	48.9	50.5	51.6	53.3	53.4	54.6	55.1	56.4
2000	3327	4153	AN	BSF		50.3	51.8	52.7	54.3	54.3	55.4	55.8	57.2
2001	2985	4020	D	JLF		50.8	52.0	53.0	54.6	54.4	55.6	56.0	57.6
2002	2200	4297	D	JLF	27.4%	50.1	51.5	52.6	54.3	54.1	55.2	55.7	57.2
2003	2558	4537	AN	BSF	23.0%	50.1	51.6	52.6	54.2	54.2	55.4	55.9	57.3
2004	3159	4060	BN	BSF	20.9%	51.8	52.5	53.5	55.1	54.8	55.9	56.4	57.7
2005	2183	4207	AN	BSF	18.5%	51.2	52.3	53.2	54.7	54.8	56.0	56.4	57.7
2006	3035	4057	W	BND	15.4%	49.6	50.9	51.7	53.1	53.3	54.7	55.0	56.3
2007	3205	3901	D	BSF	21.1%	51.5	52.5	53.3	55.0	54.8	55.7	56.2	57.4
2008	1879	2954	C	CCR	17.5%	53.1	53.8	54.6	56.6	55.9	56.9	57.4	58.8
2009	1384	2998	D	CCR	33.5%	51.9	53.0	54.1	55.9	55.6	56.8	57.2	58.8
2010	1774	4391	BN	JLF	37.5%	49.5	51.2	52.2	54.0	54.0	55.2	55.6	57.1
2011	3319	4266	W	JLF	48.6%	49.7	51.0	52.1	53.8	53.8	55.0	55.5	56.7
2012	3341	4440	BN	JLF	26.9%	49.7	51.3	52.4	54.3	53.9	55.0	55.5	56.9
2013	2592	3788	D	AND	15.1%	52.0	53.0	54.0	55.8	55.4	56.3	56.6	58.4
2014	1906	2409	C	CCR	5.6%	54.3	55.7	56.9	58.8	58.0	59.4	59.8	61.8
2015	1157	2662	C	CCR	4.2%	52.9	55.2	56.7	58.8	58.1	59.5	60.1	61.6
Avg	2407	3783			23.6%	51.0	52.3	53.3	55.0	54.8	56.0	56.4	57.9
Difference from CCR7DADM						-4.0	-2.7	-1.7		-0.2	1.0	1.4	2.9

Sacramento River Water Quality Model

Drought conditions over the last four years have highlighted the uncertainties in Reclamation's Sacramento River Water Quality Model (SRWQM) and its inability to meet the regulatory requirements outlined in the CVP/SWP operations Opinion. The SRWQM has a difficult time reflecting actual release temperature and conditions when the critical reservoir thermocline of about 52^{o}F approaches the elevation of the temperature control device (TCD) side gates and/or reservoir outlet works. Given the significant simplification of the input data (which is derived from a 12-month operations outlook), the unknowns regarding future meteorological conditions, and the fact that the actual TCD does not have infinite adjustability, the model can only realistically provide a broad brush picture of future operations, but cannot provide sufficient precision to determine future operations.

However, model improvements have been made over time using lessons learned from previous years. For example, due to the higher ambient air temperature in the past few years, in 2015 Reclamation began using more conservative (*i.e.*, warmer) meteorological forecasts from the local 3-month temperature outlook (L3MTO) rather than continuing to use average temperature as an input to the Sacramento River water temperature profile. Additionally, in 2014, the upper 5 to 6 miles of the Sacramento River read 0.6^{o}F warmer than the model, so in 2015 Reclamation adjusted the model 0.6^{o}F for better accuracy.

NMFS 2016 Sacramento River Suggested Model Inputs and Temperature Criteria Adjustments

Given the poor performance and uncertainties associated with Reclamation's model and the extreme importance to manage for higher juvenile winter-run survival during the temperature management season this year, NMFS proposes some buffers to help address the unavoidable uncertainty in temperature model and potential adjustments to the Sacramento River temperature criteria: (1) continue to use the more conservative (*i.e.*, warmer) L3MTO meteorological forecast input using an average of 2014 and 2015 meteorological data; (2) use 75% and 99% hydrological forecasts (in addition to the 50% and 90%) with additional weight to El Niño hydrological years to more accurately reflect the current hydrology; (3) apply a Shasta Reservoir temperature profile stratification scenario from the historical record that shows a steep cold water decline in the spring (*e.g.*, what happened in 2015); (4) meet an end of May Shasta Reservoir storage of at least 4.0 MAF; and (5) use the EPA (2003) recommendation of 55°F 7DADM metric and applying it to the Bonneyview Bridge (CCR) TCP.

Recognizing the difficulty of changing the regulatory compliance from a DAT to a 7DADM, NMFS analyzed to see what the downstream TCP equivalency would be. Over an 18-year period (1998-2015), CCR 7DADM tracked pretty closely to Balls Ferry (BSF) DAT [BSF DAT was 0.2°F cooler than the CCR 7DADM and the JSF DAT was 1.0°F warmer than the CCR 7DADM (Table 1)] during the temperature management season, except for 2008, 2009, and 2012 to 2015 (*i.e.*, dry and critically dry years), where CCR 7DADM tracked somewhere between BSF DAT and Jellys Ferry (JLF) DAT (Figure 2). Therefore a 55°F CCR 7DADM would be equivalent to a 56°F JLF DAT. Based upon this information, NMFS recommends a TCP of not in excess of 56°F DAT at JLF.

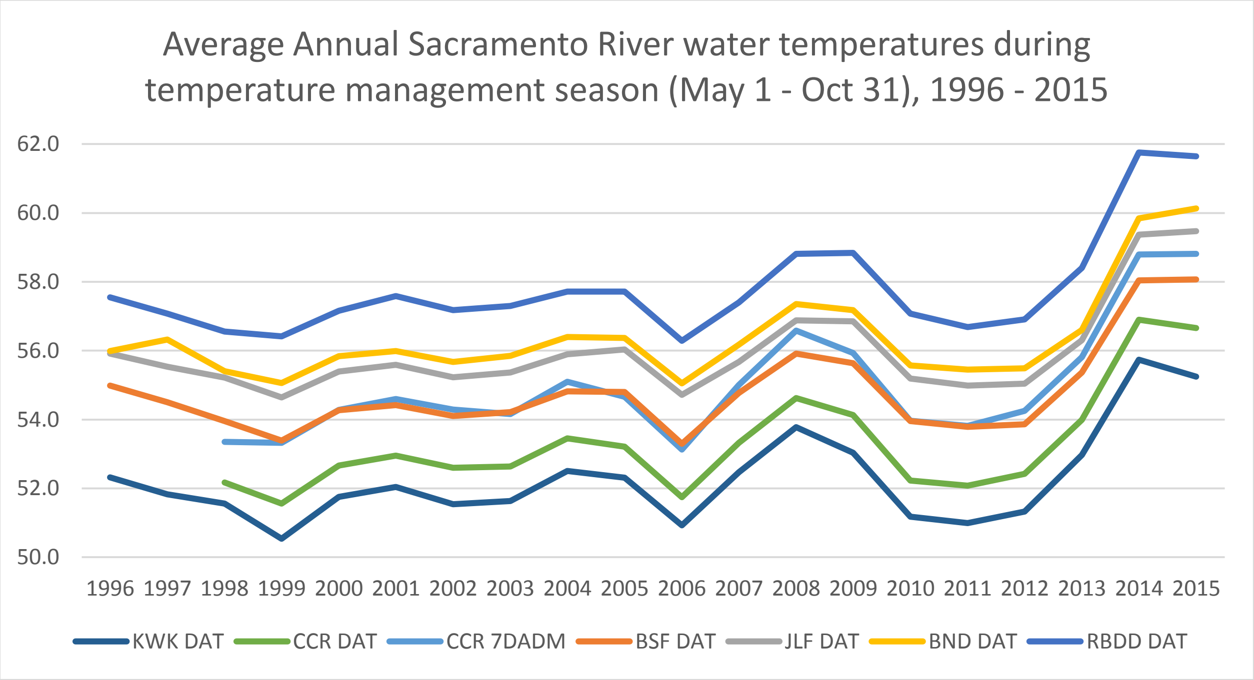

Figure 2. Average annual Sacramento River water temperature during the temperature management season (May 1 – Oct 31), 1996-2015.

2016 February Forecast from the February Update to the Central Valley Project and State Water Project 2016 Drought Contingency Plan[1]

On February 19, 2016, Reclamation released its updated operational forecasts using 50%, 90%, and 99% exceedance runoff forecasts based on the hydrological conditions as they existed on February 1, 2016. The base assumptions include utilizing existing storage conditions; actual precipitation and runoff occurring to date; future precipitation, accretions, depletions, and projected water supply deliveries based on historical statistics; meeting existing water quality standards; and current biological opinion reasonable and prudent alternatives. For these forecasts, the supplies available to the Sacramento River Settlement Contractors, San Joaquin River Exchange Contractors, and Central Valley Project Improvement Act Level 2 Refuge supplies would be consistent with a “Shasta Normal” supply for the 50% and 90% forecasts, and consistent with a “Shasta Critical” supply in the 99% forecast. In addition, the timing of diversion patterns for the Sacramento River Settlement Contractors was assumed to be adjusted (similar to last year’s operations) and allow for lower Keswick releases in April and May.

According to Reclamation’s 90% hydrological exceedance 2016 February Forecast (Table 2), the forecasted EOA storage for Shasta Reservoir is approximately 3.45 MAF. According to Reclamation’s potential for meeting a Sacramento River water temperature compliance point target[2] of 56^{o}F DAT at Jellys Ferry, there needs to be an EOA storage of at least 4.0 MAF (Figure 3). According to the 1996 to 2015 historical record (Table 1), an EOA storage of at least 4.2 MAF was necessary in order to meet the Jelly’s Ferry TCP in 4 out of 7 years. Therefore, based on the currently proposed monthly average releases from Keswick Dam, Reclamation will not be able to meet a TCP of not in excess of 56°F DAT at JLF.

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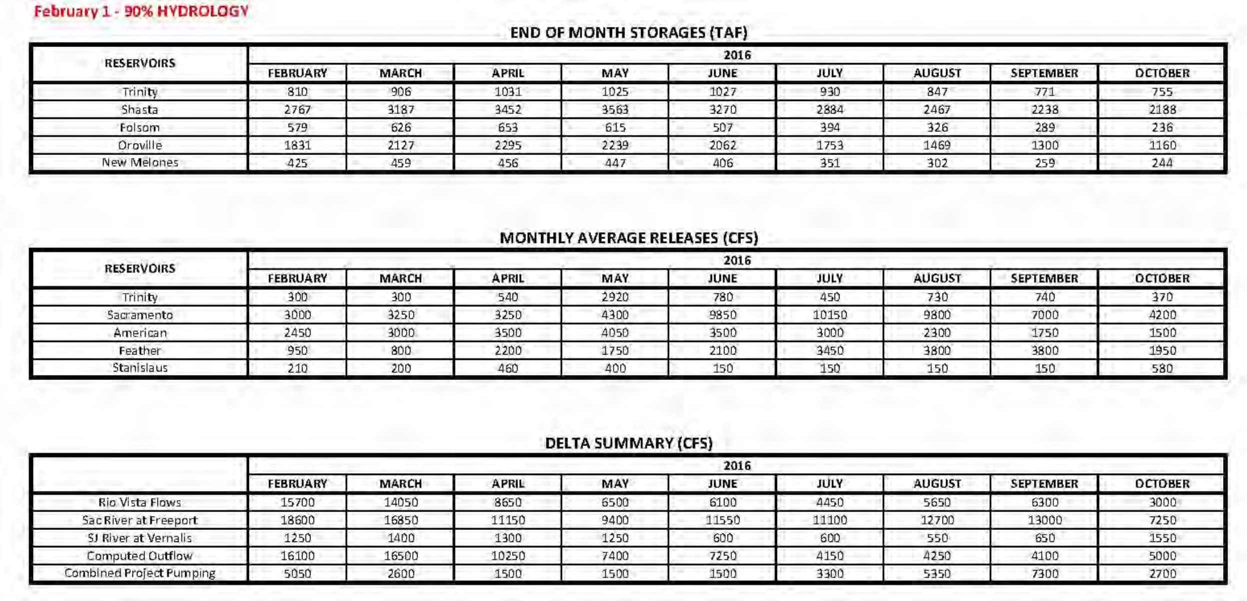
[1] http://www.waterboards.ca.gov/waterrights/water_issues/programs/drought/tucp/docs/2016dcpfebnovadd1.pdf, addendum 1

[2] Note: The CVP/SWP operations Opinion states that Reclamation shall meet a temperature compliance point *not in excess* (emphasis added) of 56^{o}F, not a target of 56^{o}F.

Table 2. 2016 February Forecast



February 1 - 90% HYDROLOGY

END OF MONTH STORAGES (TAF)

RESERVOIRS	2016								
	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER
Trinity	810	906	1031	1025	1027	930	847	771	755
Shasta	2767	3187	3452	3563	3270	2884	2467	2238	2188
Folsom	579	626	653	615	507	394	326	289	236
Oroville	1831	2127	2295	2239	2062	1753	1469	1300	1160
New Melones	425	459	456	447	406	351	302	259	244

MONTHLY AVERAGE RELEASES (CFS)

RESERVOIRS	2016								
	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER
Trinity	300	300	540	2920	780	450	730	740	370
Sacramento	3000	3250	3250	4300	9850	10150	9800	7000	4200
American	2450	3000	3500	4050	3500	3000	2300	1750	1500
Feather	950	800	2200	1750	2100	3450	3800	3800	1950
Stanislaus	210	200	460	400	150	150	150	150	580

DELTA SUMMARY (CFS)

	2016								
	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER
Rio Vista Flows	15700	14050	8650	6500	6100	4450	5650	6300	3000
Sac River at Freeport	18600	16850	11150	9400	11550	11100	12700	13000	7250
SJ River at Vernalis	1250	1400	1300	1250	600	600	550	650	1550
Computed Outflow	16100	16500	10250	7400	7250	4150	4250	4100	5000
Combined Project Pumping	5050	2600	1500	1500	1500	3300	5350	7300	2700

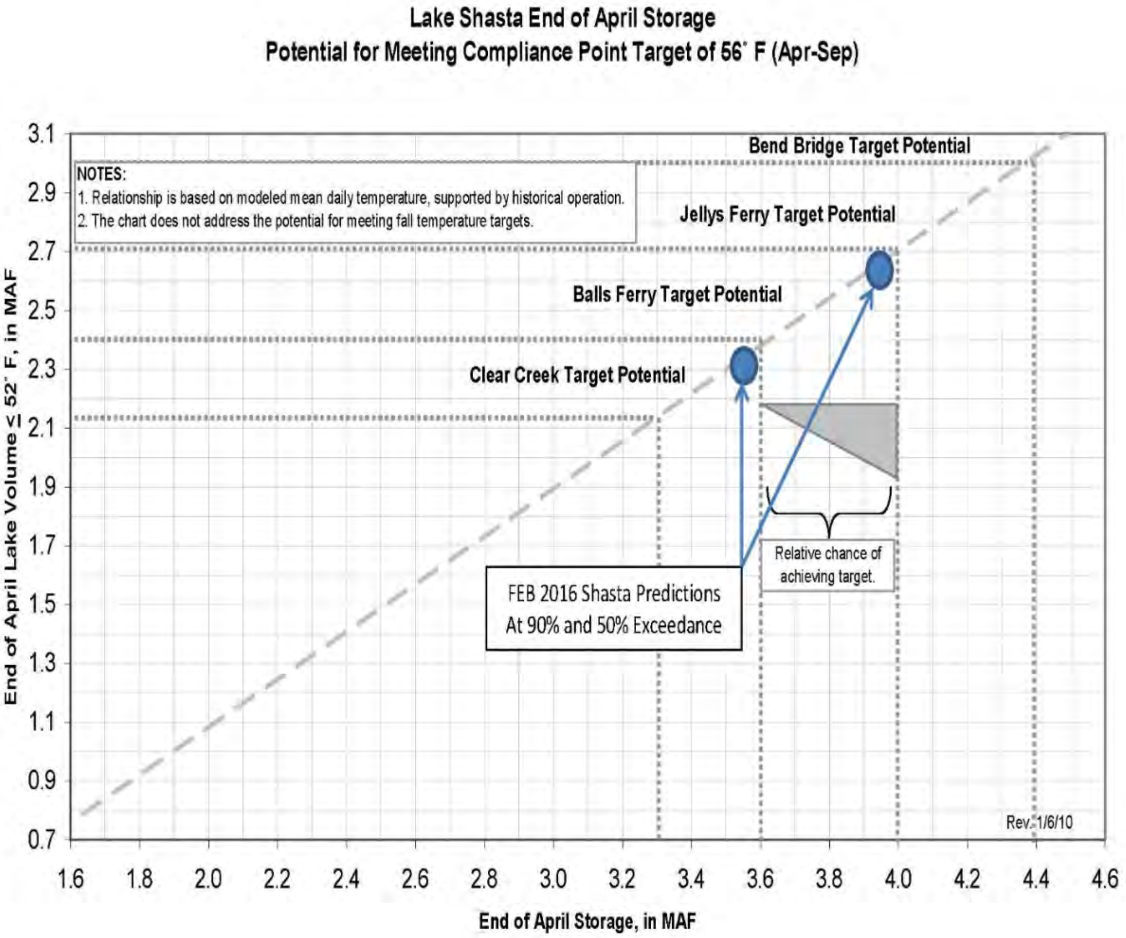


Figure 3. Lake Shasta End of April Storage Potential for Meeting Compliance Point Target.

On March 15, 2016, NMFS received from Reclamation a preliminary set of Sacramento temperature model results targeting water temperatures at Keswick Dam release point and CCR based on the February 1, 2016, hydrologic conditions and forecasted river inflow. According to the 90% exceedance hydrology, Reclamation's proposed Keswick Dam monthly average releases for May through November (Table 2), and targeting 52°F DAT at the Keswick release point[3] (KWK), Reclamation would only be able to meet 52°F DAT at KWK until a couple of days before August 23rd (Figure 4). After that date, the cold water pool in Shasta Reservoir would be depleted and/or inaccessible and the DAT at KWK would increase to more than 56°F for the rest of the temperature management season.

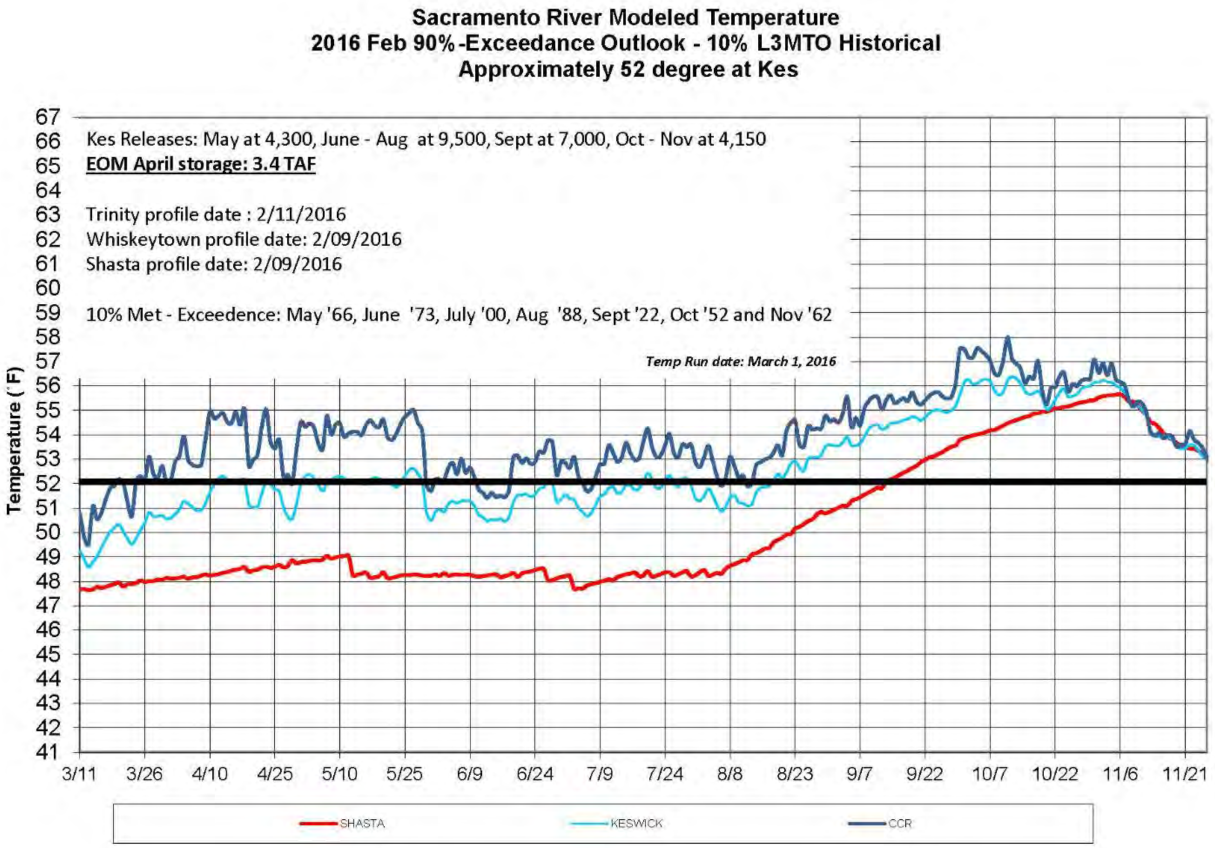


Figure 4. Reclamation's Sacramento River Modeled Temperature Results using the 2016 February 90% exceedance outlook, historical 10% local 3-month temperature outlook meteorology, Reclamation's proposed Keswick Dam monthly average releases for May through November, and targeting approximately 52°F DAT at KWK.

NMFS-SWFSC modeled the same operational scenario using their River Assessment for Forecasting Temperatures (RAFT) model. Their results were similar to Reclamation's temperature model results in that Reclamation would only be able to meet a 52°F DAT at KWK until then end of August (Figure 5). Again, after that, the cold water pool in Shasta Reservoir

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[3] NMFS and Reclamation agreed to a surrogate of 52°F DAT at KWK in lieu of 56°F DAT at JLF. See Table 1 for the correlation of KWK DAT to JLF DAT over the last 20 years.

would be depleted and/or inaccessible and DAT at KWK would increase to more than 56°F for the rest of the temperature management season.

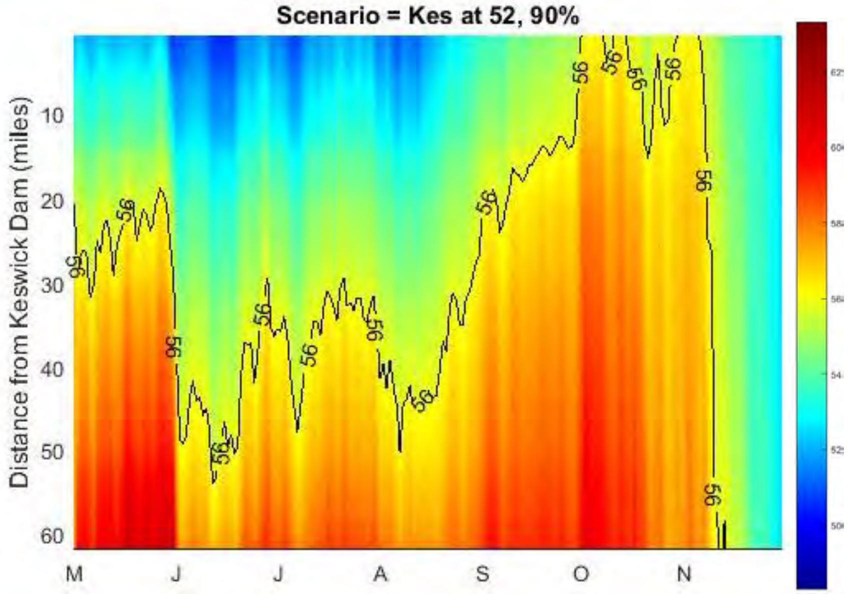


Figure 5. NMFS-SWFSC RAFT model results using the 2016 February 90% exceedance outlook, historical 10% local 3-month temperature outlook meteorology, Reclamation's proposed Keswick Dam monthly average releases for May through November, and targeting approximately 52°F DAT at KWK.

Additionally, the NMFS-SWFSC ran their temperature mortality model under this operational scenario (Figure 6). Egg-to-fry survival values start to decline for those redds that were constructed in mid-June. The survival values continue to decline further throughout the temperature management season as suitable temperatures are not able to be maintained throughout the egg incubation and fry emergence periods for the later spawners. The mean cumulative temperature dependent mortality based on this scenario is 30.5% (95% CI 0.157-53.63%).

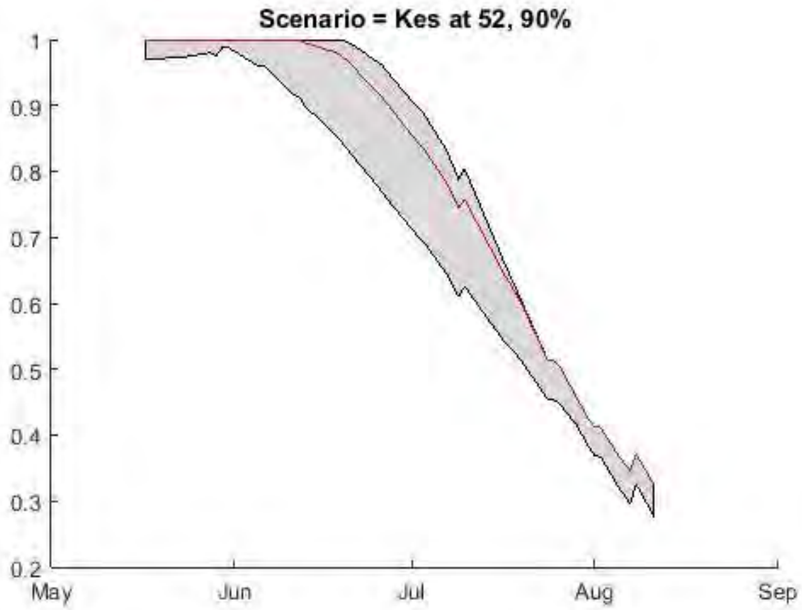


Figure 6. NMFS-SWFSC temperature mortality model results using the 2012-2015 redd distribution to calculate survival values (mean in red, 10% and 90% confidence intervals shaded grey)

In order to meet a TCP of not in excess of 56°F DAT at JLF (or alternatively, 52°F DAT at KWK), NMFS recommended that Reclamation model the following operational scenario and Keswick Dam release schedule for the February forecast (Table 3):

- Target an end of May Shasta storage of 4 MAF.
- Minimum Keswick Dam release of 3,250 cfs through May.
- Stable Keswick Dam release of 7,000 cfs from June through mid-October (or complete winter-run emergence).
- Immediately after complete winter-run emergence, reduce Keswick Dam releases, per ramping rates, to 4,000 cfs through January 2017 or through complete fall-run emergence.
- Use meteorological data from 2015.

Table 3. NMFS Scenario Flow Schedule

End of the Month Storage										
		Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Shasta		2766	3186	3451	3627	3503	3311	3066	2837	2707
Monthly River Releases (TAF/cfs)										
		Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Sacramento	TAF	187	200	193	200	417	430	430	417	338
	cfs	3250	3250	3250	3250	7000	7000	7000	7000	5500

NMFS calculated that this new Keswick Dam release schedule scenario would equate to a savings of 506 TAF (Table 4), ensuring that there is enough cold water storage to last throughout the temperature management season and resulting in EOS storage at 2.84 MAF.

Table 4. Reclamation's Proposed Keswick Dam Release Schedule Compared to NMFS Scenario for Keswick Dam Release Schedule

		Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Total
Reclamation	**End of Month Storage (TAF)**	2767	3187	3452	3563	3270	2884	2467	2238	2188	
	Monthly Releases Average (CFS)	3000	3250	3250	4300	9850	10150	9800	7000	4200	
	Monthly Releases (TAF)	173	200	193	264	586	624	603	417	258	
NMFS	**End of Month Storage (TAF)**	2766	3186	3451	3627	3503	3311	3066	2837	2707	
	Monthly Average Releases (CFS)	3250	3250	3250	3250	7000	7000	7000	7000	5500	
	Monthly Releases (TAF)	187	200	193	200	417	430	430	417	338	
Savings	**Monthly Releases (TAF)**	-14	0	0	65	170	194	172	0	-80	506

Reclamation ran their Sacramento River Water Quality Model based on the NMFS scenario for Keswick Dam release schedule (Figure 7). The results show that 52°F DAT target at KWK can be achieved throughout the temperature management season with some occasional exceedances.

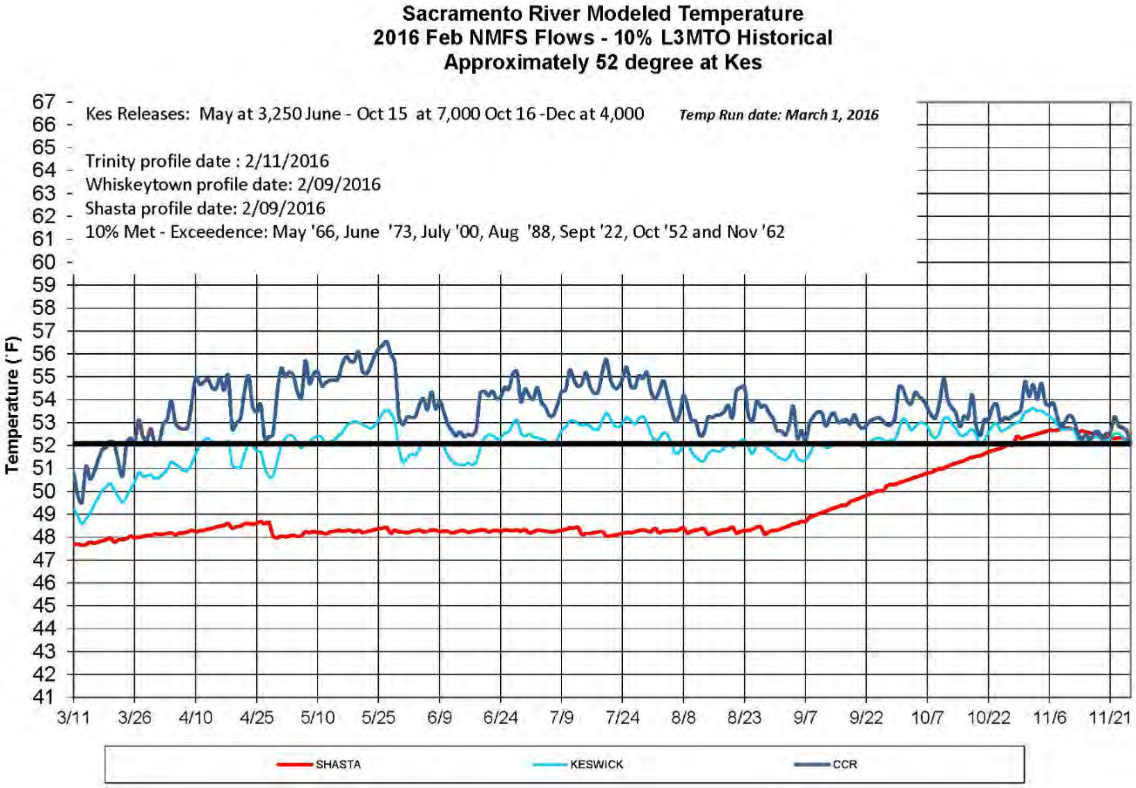


Figure 7. Reclamation's Sacramento River Modeled Temperature Results using the 2016 February 90% exceedance outlook, historical 10% local 3-month temperature outlook meteorology, NMFS-scenario for Keswick Dam monthly average releases for May through November, and targeting approximately 52°F DAT at KWK.

The NMFS-SWFSC RAFT model presented similar results, that a 52°F DAT target at KWK can be achieved throughout the temperature management season with some occasional exceedances. (Figure 8).

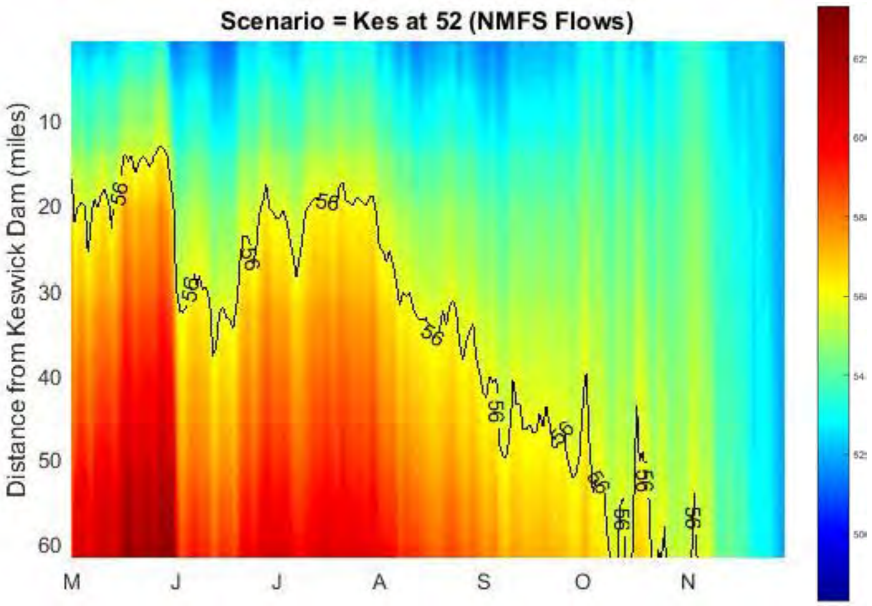


Figure 8. NMFS-SWFSC RAFT model results using the 2016 February 90% exceedance outlook, historical 10% local 3-month temperature outlook meteorology, NMFS scenario for Keswick Dam monthly average releases for May through November, and targeting approximately 52ºF DAT at KWK.

The NMFS-SWFSC temperature mortality model under this operational scenario (Figure 9) shows a much improved egg-to-fry survival compared to Reclamation's proposed Keswick Dam monthly average release schedule, as temperature has relatively little effect on mortality. The mean cumulative temperature dependent mortality based on this scenario is 5.4% (95% CI 0.88-37.93%).

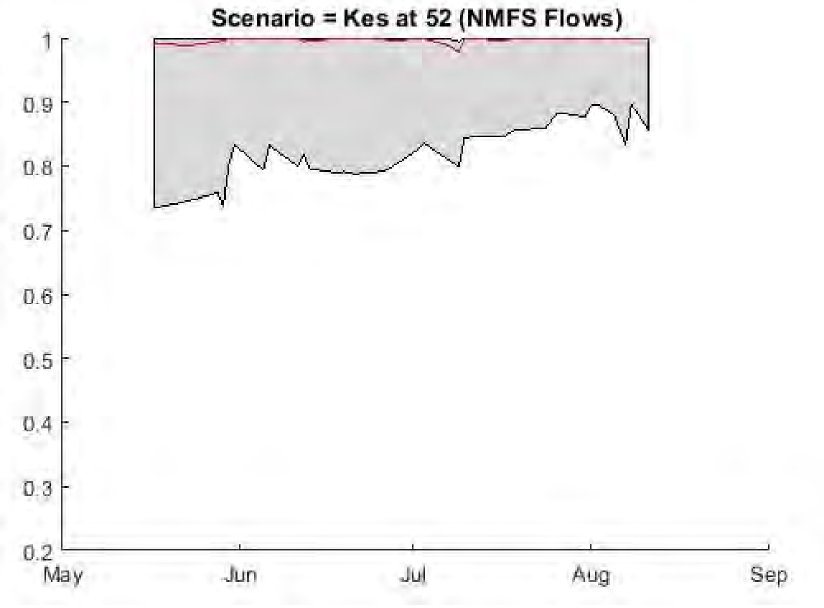
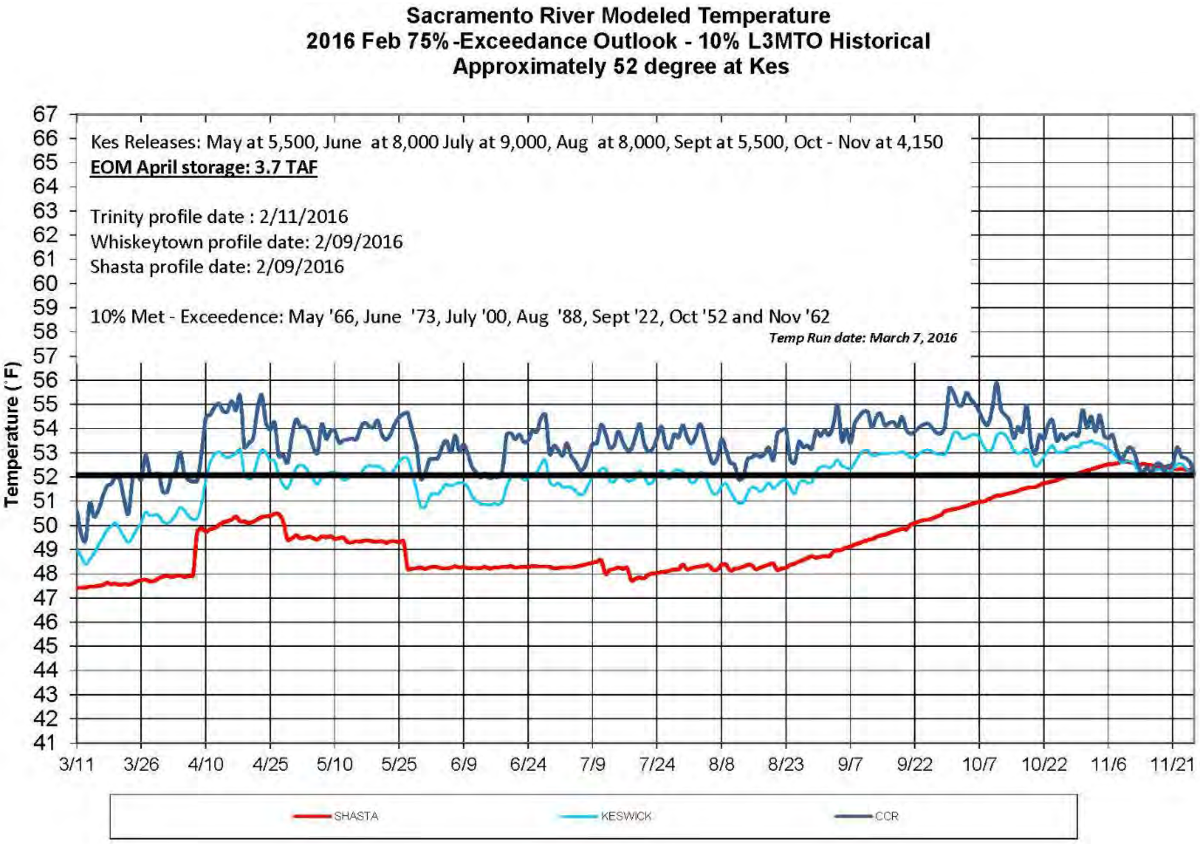


Figure 9. NMFS-SWFSC temperature mortality model results using the 2012-2015 redd distribution to calculate survival values (mean in red, 10% and 90% confidence intervals shaded grey)

Reclamation also ran their Sacramento River Water Quality Model using the 75% exceedance outlook and their proposed Keswick Dam monthly average release schedule. Similar to the 90% hydrological exceedance, Reclamation would only be able to meet 52°F DAT at KWK until about the end of August (Figure 9). After that, KWK DAT would rise to a peak of about 54°F through the end September and October.



Sacramento River Modeled Temperature
2016 Feb 75% -Exceedance Outlook - 10% L3MTO Historical
Approximately 52 degree at Kes

Kes Releases: May at 5,500, June at 8,000 July at 9,000, Aug at 8,000, Sept at 5,500, Oct - Nov at 4,150
EOM April storage: 3.7 TAF

Trinity profile date : 2/11/2016
Whiskeytown profile date: 2/09/2016
Shasta profile date: 2/09/2016

10% Met - Exceedence: May '66, June '73, July '00, Aug '88, Sept '22, Oct '52 and Nov '62
Temp Run date: March 7, 2016

Figure 9. Reclamation's Sacramento River Modeled Temperature Results using the 2016 February 75% exceedance outlook, historical 10% local 3-month temperature outlook meteorology, Reclamation's proposed Keswick Dam monthly average releases for May through November, and targeting approximately 52°F DAT at KWK.

Results of NMFS-SWFSC RAFT under this scenario were similar to that of the SRWQM (Figure 10), showing that a 52°F DAT target at KWK can be achieved throughout most of the temperature management season with warmer water at KWK at the end of September and beginning of October.

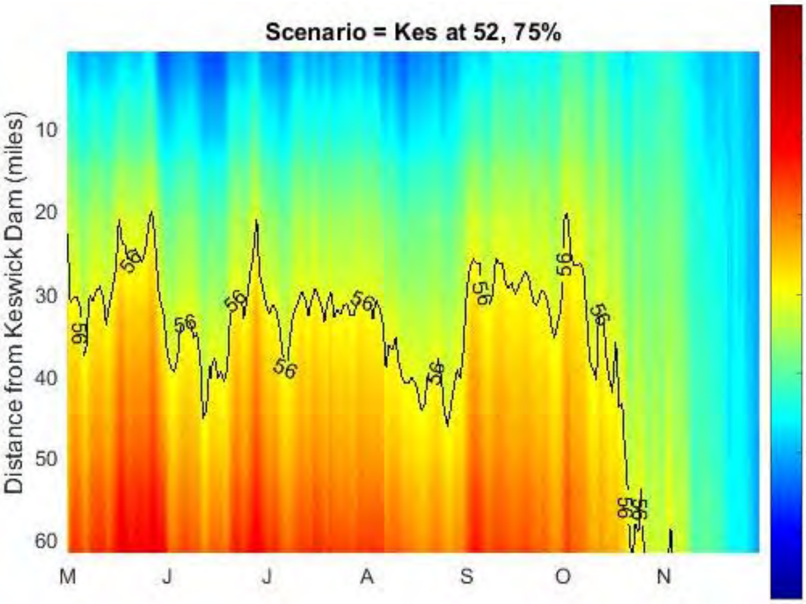


Figure 10. NMFS-SWFSC RAFT model results using the 2016 February 75% exceedance outlook, historical 10% local 3-month temperature outlook meteorology, Reclamation's proposed Keswick Dam monthly average releases for May through November, and targeting approximately 52ºF DAT at KWK.

Results of NMFS-SWFSC temperature mortality model under the 75% exceedance outlook (Figure 11) shows a decreased egg-to-fry survival compared to the NMFS scenario for those spawners after early July, but much better egg-to-fry survival compared to the 90% exceedance outlook. The mean cumulative temperature dependent mortality based on this scenario is 6.3% (95% CI 0.84-36.82%).

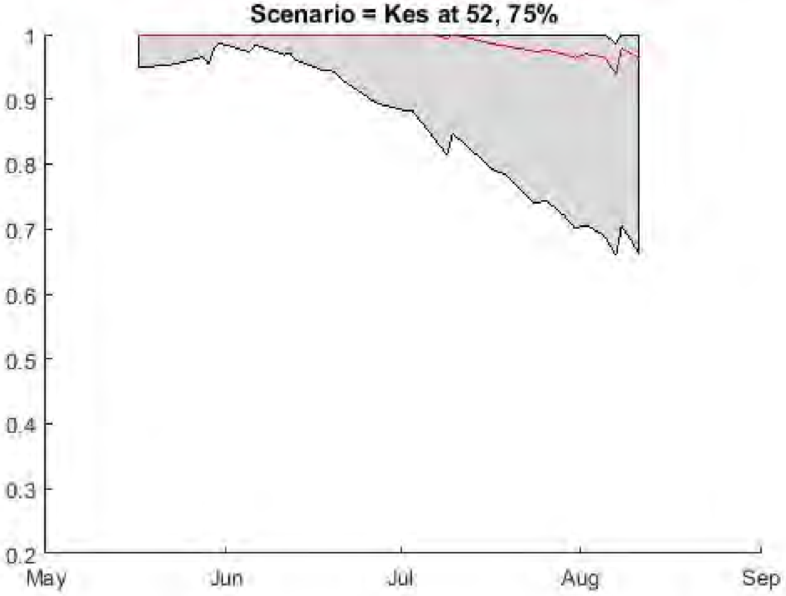


Figure 11. NMFS-SWFSC temperature mortality model results using the 2012-2015 redd distribution to calculate survival values (mean in red, 10% and 90% confidence intervals shaded grey)

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Attachment

Modeling temperature dependent mortality of winter-run Sacramento River Chinook salmon.

Benjamin Martin, Sara John, Andrew Pike, Jason Roberts, Eric Danner

Model development

Overview

We developed a semi-mechanistic/statistical model of temperature-dependent survival of winter-run Chinook in the Sacramento River. Our modeling approach makes use of information on the timing and distribution of redd locations taken from aerial surveys from 1996-2015. For each known redd we extract a temperature exposure profile that redd would have experienced from fertilization to emergence using RAFT, a spatially explicitly hydraulic model of the Sacramento River (Pike et al. 2013). For each known redd, we then apply a temperature-dependent mortality model with daily time steps to calculate the probability of survival from fertilization to emergence. We then calculated predicted survival within a year by aggregating the survival of all redds within a year, and compare the predicted survival in a year to observed yearly survival from egg-to-fry (ETF) estimated by the US Fish and Wildlife serve from 1996-2015. Finally we estimate the parameters of our daily temperature-dependent mortality model by minimizing the deviations between predicted and observed survival across years.

Redd location and timing

The timing and location of WR redds was determined from aerial helicopter surveys conducted by CDFW on a semi-weekly basis. During each aerial survey the location and estimated number of newly formed redds was recorded.

RAFT temperature model

We extracted temperature exposure profiles for all redds located in CDFW aerial surveys using RAFT, River Assessment for Forecasting Temperatures (RAFT). RAFT is a 1-dimensional stream temperature model that predicts thermal impacts of reservoir releases on the downstream environment (Pike et al. 2013). RAFT uses a process-based approach by computing heat transfer due to advection, longitudinal dispersion, atmospheric and subsurface heat-exchange, and tributary inputs to simulate temperatures and flow at a spatiotemporal resolution of 1km and sub-hourly timesteps. The CDFW aerial survey redd location data were converted to RAFT river kilometer. For each redd, a daily temperature exposure profile was complied from the date the redd was first sighted (fertilization), through to emergence. The number of days from fertilization to emergence was calculated using a temperature-dependent development model (Zueg et al. 2009), where the rate of development in day i is given by:

$$D_{i+1} = D_i + (0.00058 \times T - 0.018)$$

where T is the mean daily RAFT temperature in Fahrenheit. At fertilization D=0, and Chinook emerge on the day D exceeds 1.

Temperature-dependent mortality model

We applied a daily temperature dependent mortality model to all redds based on the mean daily temperature exposure profiles calculated from RAFT (Figure 1). The temperature-dependence of survival in our model is determined by two parameters. T_{crit}, the temperature below which there is no mortality due to temperature. Above T_{crit}, we assume the instantaneous mortality rate increases linearly with increasing temperature with a slope equal to b_T, the second parameter:

$$h_i = b_T \max(T_i - T_{crit}, 0)$$

T_i is the mean daily temperature experienced by a given redd on the ith day of its development. The survival probability during the ith day of:

$$s_i = e^{-h_i}$$

Survival throughout the entire embryonic period is given by the product of the daily temperature dependent survival probabilities from hatching to emergence, multiplied by the temperature-independent survival rate, μ.

$$S = \mu \prod_{i=1}^{n} s_i$$

The value of μ represents the expected winter-run survival to RBDD in the absence of adverse temperature effects. We hypothesized that due to limited optimal habitat for spawning, mean redd quality decreases with increasing female spawner density. Thus we evaluated whether female spawner density affected ETF survival by evaluating a models including a density dependence term in the background survival rate:

$$\mu = \mu_0 + \mu_1 N$$

where N is the number of winter run spawning females determined from carcass surveys. Annual estimates for ETF survival were calculated by taking the average of the redd-specific survival rates of all redds within a year.

The major assumptions of our model are that WR Chinook are equally sensitive to temperature throughout their development from fertilization to emergence. In other words, the survival of pre-eyed embryos, eyed embryos, and alevin are all equally affected by temperature (T_{crit} and b_T parameters are constant throughout development). Additionally we assume that temperature-dependent mortality in day *i* depends only on the mean daily temperature on that day, and is independent of the temperature on preceding days. For example, if T_{crit} is exceeded on 7 days during development by 1 degree, the survival rate predicted by our model is independent of whether the 7 days above T_{crit} are consecutive or spread evenly throughout the development period. These assumptions are made because insufficient data are available to specify more complex, parameter rich, models that allow temperature-dependent survival to vary with time or development stage. Chinook fry are much less sensitive to elevated temperatures than pre-emergence stages. For example Chinook fry can be reared successfully at 68F (Fangue unpublished), while rearing embryos at 64F results in nearly 100% mortality. We therefore only included the effect of temperature on survival from fertilization to emergence. Post-emergence mortality is figured into the background survival rate (μ).

Parameter estimation

Model parameters were estimated via non-linear least squares. We searched parameter space for the parameter set that minimized the squared deviation between model predicted winter-run ETF survival to RBDD, and estimates from USFWS from 1996-2015. Because the dependent variable are proportions (fraction survival), and thus bounded between 0 and 1, we logit transformed the dependent variable (Warton and Hui 2011). This ensured predictions cannot exceed possible values (e.g. negative survival), and normalized residual error. Thus data were transformed such that:

$$p_i^* = \log\left(\frac{p_i}{1-p_i}\right)$$

$$x_i^* = \log\left(\frac{x_i}{1-x_i}\right)$$

where p_i and x_i are the predicted and observed fractional survival in year i.

We used a numerical optimization routine in Matlab (fminsearch) to search parameter space for the parameter set (θ) that minimized the sum of squares between predicted and observed winter-run survival:

$$SSQ(\theta) = \sum_{i=1}^{n}\left(p_i^*(\theta) - x_i^*\right)^2$$

Uncertainty analysis

To evaluate how uncertainty in ETF survival estimates affected our parameter estimates and model predictions we preformed an uncertainty analysis. Using the logit transformed yearly survival estimates we resampled yearly survival estimates from a Gaussian distribution with a mean equal to the estimated value (from the USFWS report) and a standard deviation equal to the standard error of the yearly survival estimates (calculated from the reported confidence intervals in the USFWS report). We used this method to generate 1000 randomized datasets, and then used the same model fitting techniques to estimate model parameters. We calculated 95% uncertainty intervals by using the 97.5 and 2.5% quantiles for the 1000 simulated datasets. Furthermore we used parameter estimates from the 1000 simulated data sets to construct prediction confidence intervals for mortality as a function of temperature. For each parameter set we calculated survival as a function of temperature for different exposure times (e.g. one day, one week, one month).

Comparison to laboratory data

To compare thermal tolerance estimated in laboratory studies with thermal tolerance in the field, we fit the same temperature dependent mortality model to laboratory data. Data on survival throughout the embryonic period as a function of temperature were taken from data sources compiled in Myrick and Cech (2001). We use non-linear least squares to estimate T_{crit} and b_T from laboratory data and compared the resulting predictions for survival as a function of temperature to those estimated using ETF survival data in the field.

RESULTS

The model including temperature-dependent mortality out-performed the model assuming a constant temperature independent survival probability (Table 1), rejecting the null hypothesis that yearly survival was independent of temperature (p=0.0005). Furthermore the null hypothesis that survival was independent of female spawner density was rejected (p=0.029). Altogether the full model including temperature and density dependent effects explained most of the variance in annual ETF survival ($R^2 = 0.77$).

Our analysis indicates substantial year-to-year variation in temperature dependent mortality. In most years temperature contributes negligibly to predicted ETF survival (Figure 2). In these cases, such as 2002-2003, 2007, and 2010-2012, redds were rarely if ever exposed to temperatures above T_{crit}, and survival was high. Among years with low temperature-dependent mortality, those with a high number of female spawners (2002-2007) had lower ETF survival than years with few female spawners (2010-2012). Overall we estimate that starting from a background survival rate of ~35% at very low spawner density, every additional 1000 returning females reduces survival by a little less than 2% (1.88%). As a result, the predicted background survival rate is cut in half as we move from the low (~400) to high (~9000) end of observed variation in female spawner density (Figure 3).

Although in many years temperature had little influence on ETF survival, in the years it did affect survival, the impact was substantial. Most notably, in 2014 and 2015 temperature dependent mortality alone resulted in a loss of ~77% and 85% of the population. When combined with background survival, this resulted in the extremely low ETF survival both predicted and observed in these years (~5%). These high levels of temperature dependent mortality are driven by the high value of b_T, the slope by which instantaneous mortality rate increases above T_{crit}. As a result of a high value of b_T, mortality rate increases rapidly above T_{crit}. For example there is no predicted mortality due to temperature up to around 54F (Figure 4). However above this critical temperature mortality rate increased rapidly; a week at 56F resulted in a loss of approximately 20% of the population, and a loss of 60% after a month (Figure 4).

Uncertainty analysis

Parameter estimates of T_{crit} varied between 52 and 56F (Table 2). However there was significant co-variation between T_{crit} and b_T (Figure 3). The roughly 5% of simulated datasets with high T_{crit} estimates were associated with extremely high values of b_T (the slope by which mortality increases above T_{crit}). As a result, parameter sets with a high T_{crit} predicted that mortality increased extremely rapidly above T_{crit}, such that exposure to water temperatures exceeding T_{crit} by only a fraction of a degree over short period of time, result in high mortality rates.

The model predictions for 90% of the resampled parameter values fell within a well-defined range, especially within the range of temperatures typically encountered in the upper Sacramento (50-58F) (Figure 4).

Lab vs. Field

Thermal tolerance of winter-run Chinook estimated in the field was substantially reduced relative to thermal tolerance estimated from laboratory data (Figure 6). While the estimated values for b_T were roughly similar in the lab and field, T_{crit} estimated from field data was more than 6 degrees lower in the field in the lab. Thus using lab data, our model predicts no mortality at 56F, while in the field this results in a loss 80% of the population.

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Table 1. Model comparison

Model	SSQ	df	F value	P value	R^2
Constant mortality	9.47	1			
Temperature dependent mortality	3.18	3	13.52	0.0005	0.66
Temperature and density dependent mortality	2.17	4	6.05	0.029	0.77

Table 2. The least squares estimate for the parameters in the full model are given in table 2.

Parameter	Least Squares Estimate	Resampling 95% CI
T_{crit}	53.72	52.09 – 56.25
b_T	0.0133	0.0059 - 0.557
μ_0	0.3467	0.276- 0.44
μ_1	-1.88E-05	-6.18E-6 - -3.275E-5

Figure 1. Schematic diagram of the temperature-dependent mortality model. The instantaneous daily mortality rate (*h*) is 0 when the mean daily temperature is below T_{crit}. Above Tcrit, h increases linearly with temperature with a slope, b_T.

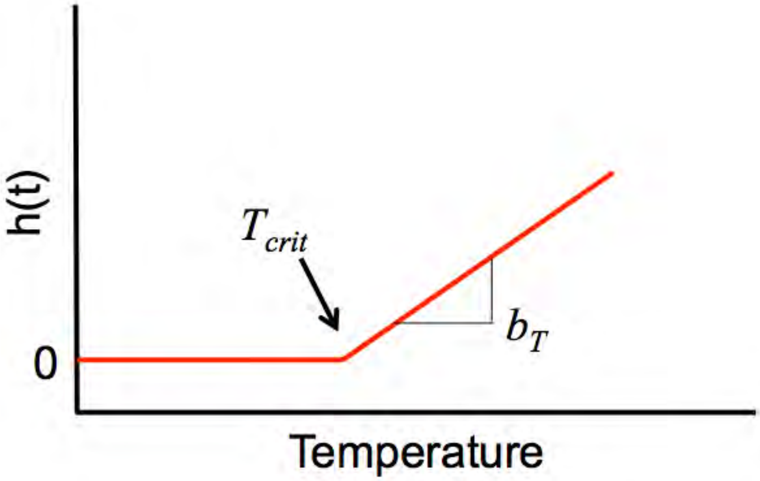

Figure 2. Observed vs. predicted survival in the full model (top and middle panels) and the predicted mortality due to temperature

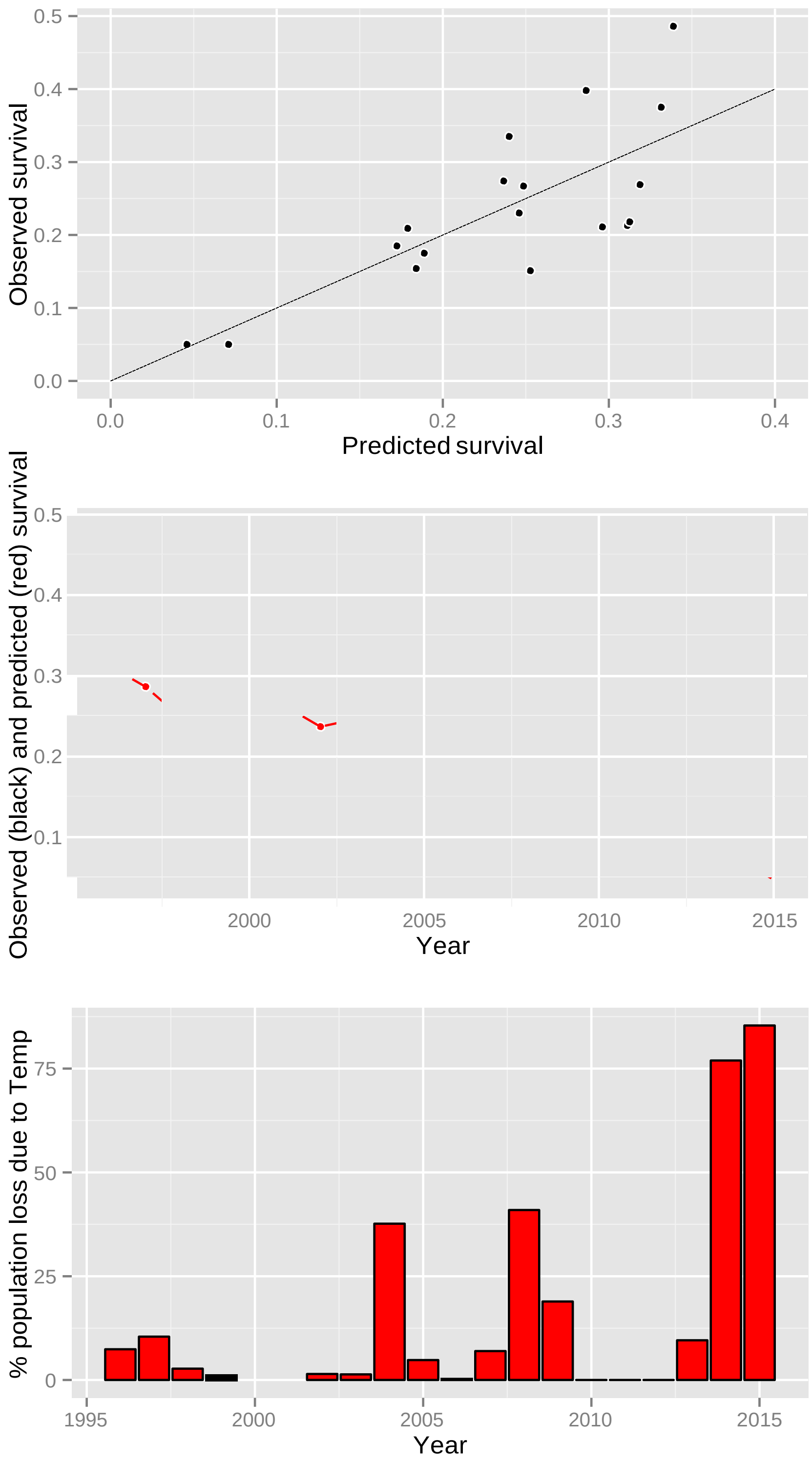

Figure 3. Influence of female spawner density on background survival rate. Panel A show the time series of the number of returning female spawners. Panel B shows the relationship between observed and predicted (red line) ETF survival and female spawner density. Panel C shows this seem relationship but with observed ETF corrected to exclude mortality due to temperature (corrected ETF = Observed ETF / (1 – fractional population loss due to temperature alone).

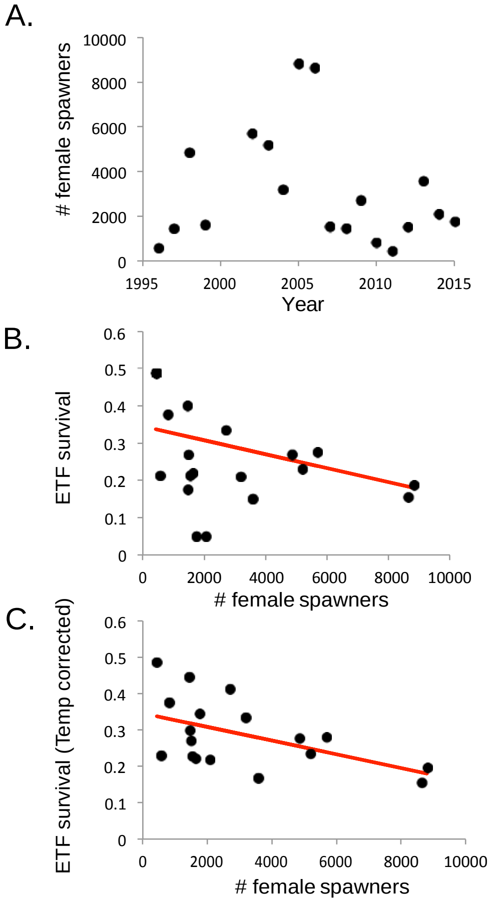

Figure 4. Predictions for mortality due to temperature exposure for 1 day, 1 week, and 1 month in the redd model. Each red line represents one of a 1000 parameter sets estimated from the resampled yearly survival dataset. The thick black line represent the median predicted value and the dashed black lines the 90 confidence intervals and the dotted lines the 95% confidence intervals.

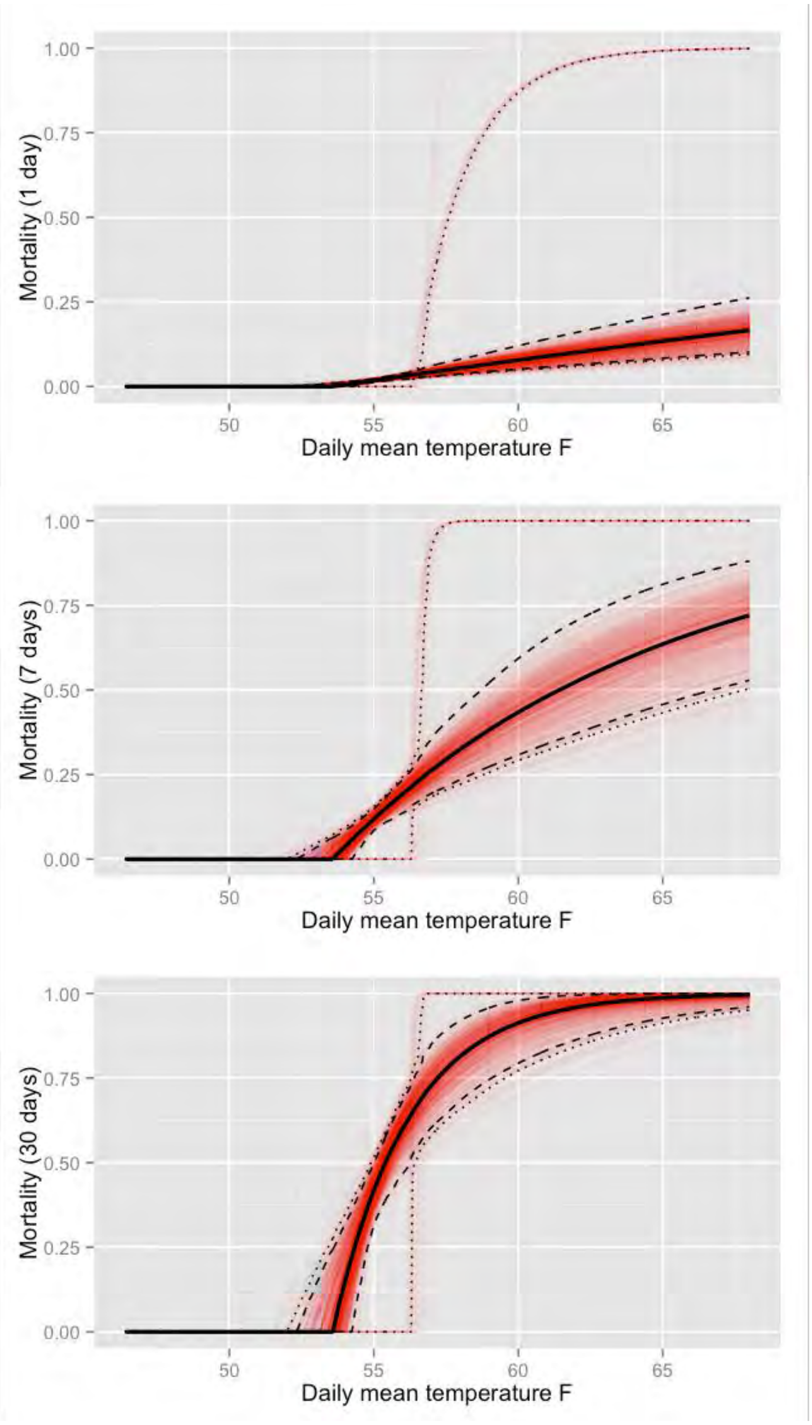

Figure 5. Parameter estimate frequency charts (diagonal) and covariance matrix in the redd temperature model.

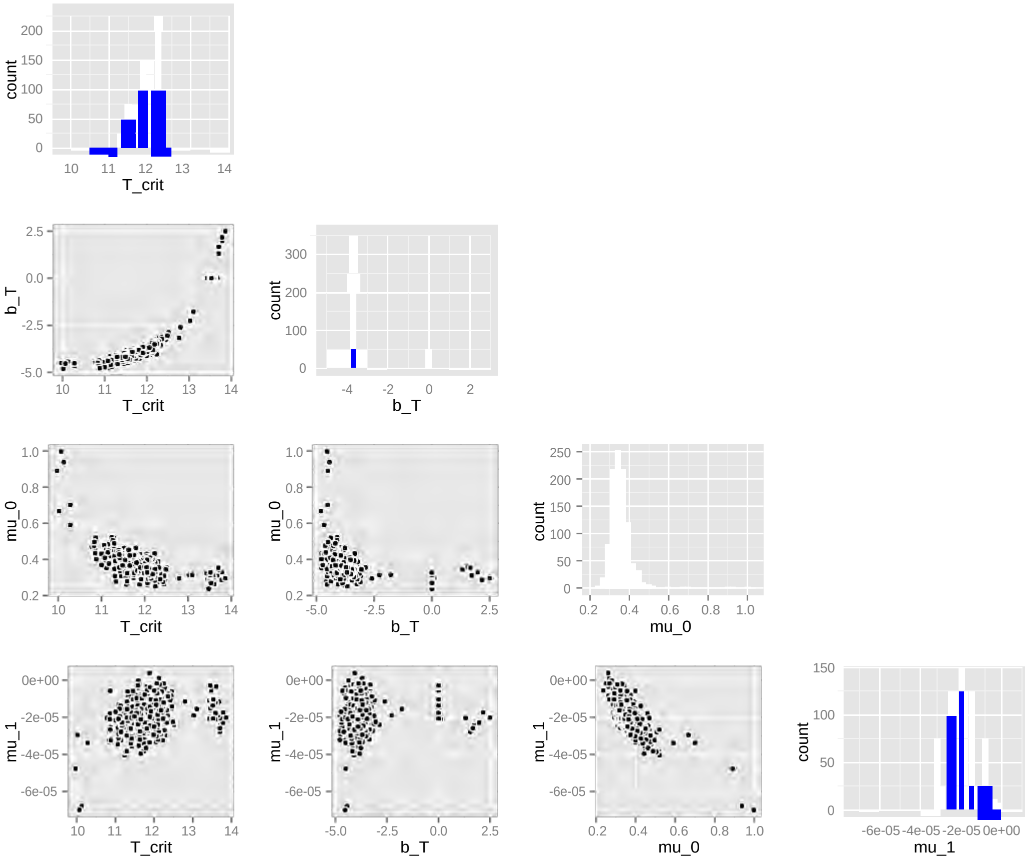

Figure 6. Temperature dependent survival estimated in the laboratory vs. field. Observed survival (black points) through the embryonic period in laboratory studies as a function temperature. The blue line represents the least-squares model fit to laboratory data. The black and red lines represents the same model but with parameters estimated from field ETF survival data (solid, median; dashed, 90% CI).