FISH PASSAGE CENTER

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MEMORANDUM

TO: John Palmer, EPA

Michele DeHart

FROM: Michele DeHart

DATE: October 31, 2016

RE: The effect of water temperature on steelhead upstream passage

In response to your request the Fish Passage Center staff has developed the following analyses. The request for analyses had four separate components as follows.

- An analysis of the effect of water temperature on upstream passage of steelhead;
- A graphical representation of the number of steelhead, chinook, and sockeye when water temperature exceeded 18°C for the past five years counts at Bonneville Dam;
- An analysis of the correlation between daily average forebay temperatures at Bonneville Dam and forebay temperatures at McNary Dam during the migration periods for sockeye, summer Chinook, fall Chinook, and steelhead over 5-day, 7-day and 9-day averages;
- A summary of data sources for evaluation and enumeration of fish harvest which would support the separation of harvest effects from environmental effects on upstream migration survival.

Each component of the request is addressed separately in the following memorandum. The overall conclusions from these analyses are summarized in the following list.

- Water temperatures exceeding 18°C had a consistent negative impact on steelhead conversion rates between Bonneville and McNary dams. Even without including harvest impacts on conversion rates, the negative impact of water temperature on conversion rate was significant.
- The proportion of Chinook, steelhead, and sockeye adults passing Bonneville Dam at temperatures greater than 18°C was calculated using adult ladder counts for 2011 – 2015. In general, a large proportion of each run was observed to pass at temperatures above 18°C.

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- As water temperature increases, steelhead upstream migration travel time increases, especially at temperatures above 18°C.
- Snake River steelhead that were transported as juveniles had significantly lower conversion rates between Bonneville and McNary dams at temperatures at and above 18°C. The negative effect of the transportation treatment on Bonneville to McNary conversion rate precluded the inclusion of transported steelhead in these analyses, since conversion rates of transported groups were significantly lower than the non-transported groups.
- Water temperatures above 18°C had the largest impact on conversion rates between Bonneville and McNary Dams. Although arrival timing does have a statistically significant impact on conversion rates, its effect is small in comparison to the negative effects of high water temperatures.
- Over time, the forebay temperature at Bonneville Dam is correlated with the forebay temperature at McNary dam in 5-, 7- and 9-day averages. However, it is noted that the 5-, 7- and 9-day averages do not reflect steelhead travel time between Bonneville and McNary dams. Steelhead travel times are significantly longer.
- Steelhead harvest rates are developed and analyzed by the Technical Advisory Committee of US v Oregon and the Joint Technical Staff of Oregon Department of Fish and Wildlife and the Washington Department of Fish and Wildlife. This group is the best source for harvest data.
- Cold water refuges should be considered with caution, since due to additional factors they may not contribute to better conversion rates between Bonneville and McNary dams.
- Water temperatures affect upstream migration travel time and therefore also potentially affecting harvest rates by increasing steelhead vulnerability to harvest.

Methods

Selecting Fish for Inclusion in Analyses

In these analyses we used PIT-tagged adult steelhead detected at Bonneville Dam between June 1st and September 15th. This date range was selected to incorporate the bulk of adult steelhead passage at Bonneville while minimizing the inclusion of holdovers (steelhead that enter the river in one year and complete their upstream migration in the following year) (Keefer et al. 2015). For the time period used in these analyses, the overall holdover rate was 1.2%.

Bonneville forebay temperature and adult PIT-tag detections from June 1 through September 15 were available at Bonneville and McNary dams for 2003 through 2015. This 13-year dataset includes a wide range of water years (i.e., flows), temperatures, and adult returns to represent steelhead passage between Bonneville and McNary Dams. Complete coverage for adult PIT-tag detection at Bonneville Dam was first implemented in return year 2002. Adult fish PIT-tag detection capability was not in place at The Dalles and John Day dams during most of this period. Detection capabilities were installed at The Dalles Dam in 2013 and are planned for installation at John Day Dam in 2017. Without PIT-tag detection at locations between Bonneville and McNary dams it is not possible to assess survival and passage at a finer scale through this reach.

The PIT-tagged steelhead utilized in this analysis originated from PIT-tag marking for research and monitoring studies in the Snake and Upper Columbia rivers. The mark groups in this analysis include hatchery and wild origin fish. For groups originating in the Snake River, some portion of PIT-tagged steelhead were subject to smolt transportation. In reviewing the upstream passage characteristics and survival of Snake River steelhead that were transported as smolts, it became apparent that fish that were transported as juveniles had much longer adult travel times and much lower survival between Bonneville and McNary dams (Keefer et al. 2008, Keefer et al. 2016) (Figure 1). Because transportation significantly decreases conversion rates at all water temperatures, including temperatures below 18°C, the Snake River transported PIT-tag group was not applicable to the primary objective of this analysis regarding the effect of water temperature on upstream survival. In addition hatchery B-run steelhead mark groups were not included in these analyses because their median arrival timing at Bonneville is after September 1st, much later than the other mark groups. In addition, B-run steelhead also appear to have a greater tendency to complete their upstream migration the following spring (Keefer et al. 2015). Table 1 shows the total number of returning PIT-tagged steelhead at Bonneville Dam by rear type and basin of origin.

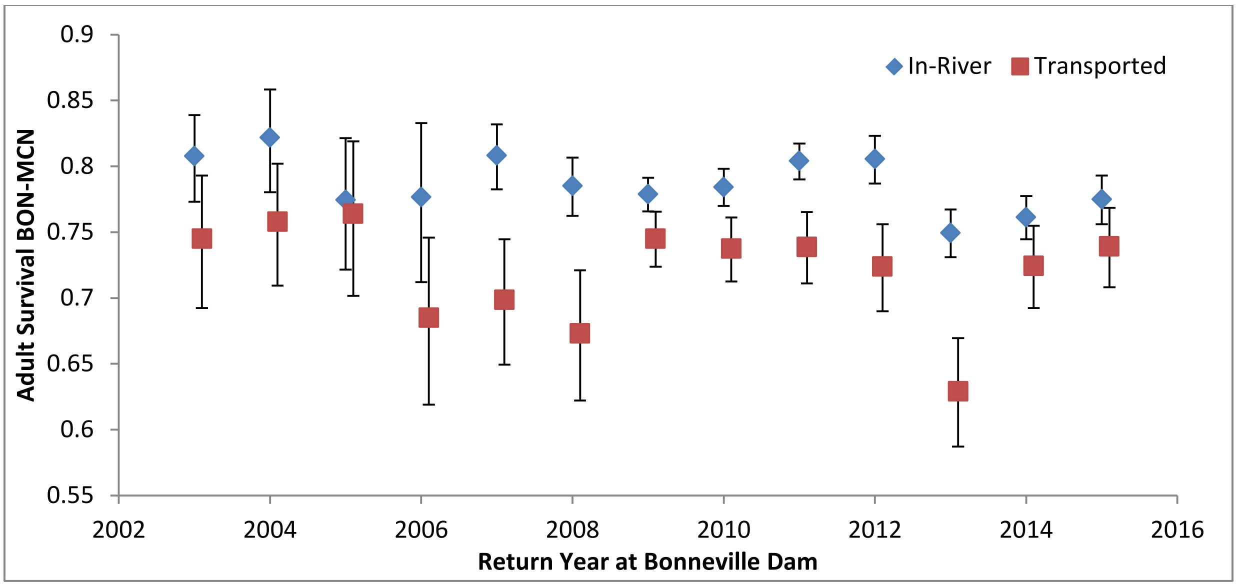

Figure 1: Survival of PIT-tagged Snake River adult steelhead, separated by juvenile migration type, between Bonneville and McNary Dams with 95% confidence intervals.

These analyses examine the effect of water temperature on upstream passage of adult steelhead in the river reach between Bonneville and McNary dams. In these analyses there has been no adjustment for harvest rate, which affects conversion rate between Bonneville and McNary dams. Although harvest may represent a significant source of mortality for the adult steelhead migration in this river reach, our analyses show that the effect of water temperature on conversion rate between Bonneville and McNary dams was still apparent.

Table 1: Counts of individual returning PIT-tagged hatchery and wild steelhead at Bonneville Dam from June 1 to September 15 by basin of origin for inclusion in analyses.

Return	Hatchery		Wild	
Year	Snake	Upper Columbia	Snake	Upper Columbia
2003	108	40	790	12
2004	154	1,491	595	9
2005	166	2,987	364	2
2006	251	3,657	172	6
2007	820	856	572	30
2008	789	507	970	49
2009	4,112	1,054	1,760	239
2010	3,126	648	1,646	215
2011	3,200	876	1,182	177
2012	2,002	864	787	118
2013	1,956	598	920	145
2014	2,612	648	1,217	191
2015	1,870	663	990	187
Total	21,166	14,889	11,965	1,380

Arrival Timing of Mark Groups

A graphical summary of the 10 year average arrival distribution of hatchery and wild-origin PIT-tagged steelhead by basin is provided in Figure 2. Wild and hatchery fish have similar arrival timing for both basins, with the exception of B-run steelhead, which are not included in the following analyses. With similar arrival timing between groups at Bonneville Dam, we can assume the initial migration conditions they encounter are comparable.

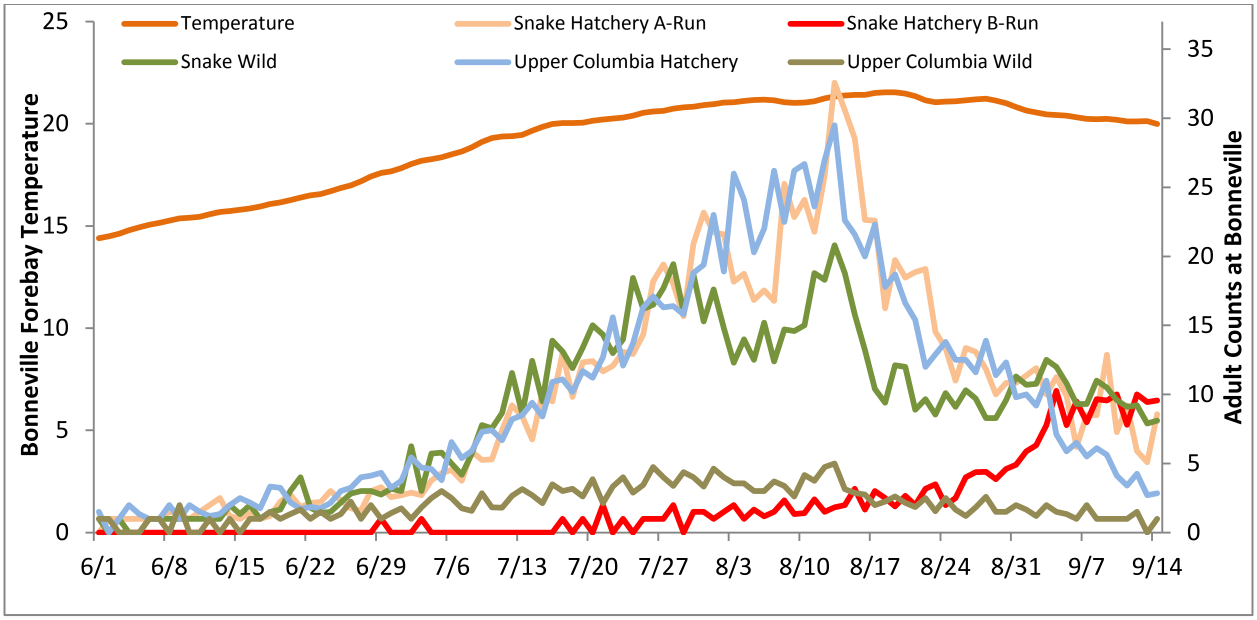

Figure 2: 10-year average temperatures (°C) in the Bonneville Dam forebay and 10 year average of PIT-tagged adult steelhead counts at Bonneville from June 1 to September 15, 2003 – 2015.

Bonneville Water Temperatures

In these analyses, Bonneville forebay temperatures are used as a measure of water temperature during upstream migration. These forebay temperatures were collected by the total dissolved gas monitor in the Bonneville forebay, which is located in a fixed location on the north end of the spillway, at a depth of approximately 14 feet. The water temperature assigned to each adult is defined as the average Bonneville Dam forebay water temperature on the day of the last PIT-tag detection of each adult at Bonneville Dam.

It is worth noting that detection of PIT-tag adults at projects between Bonneville and McNary Dams is limited. John Day Dam currently has no PIT-tag detection in the adult fishways and The Dalles Dam has only had adult detection since 2013. Therefore, it is not possible to track adult fish in their migration within this reach at a finer spatial scale. If they remain in thermal refuges for much of the migration period, the temperatures in the mainstem Columbia may not be representative of thermal exposure during that period.

Figure 3 shows the daily average temperate in the Bonneville Dam forebay over the time period of the analysis. Temperatures in the Bonneville forebay show an overall increasing trend between June 1 and early August in all years. For most of this period (2003-2015), daily temperatures in 2015 were well above all other years in the time series by 1° – 8°C. In early August of 2015 temperatures were generally above the average but within the variation of past years in the time series.

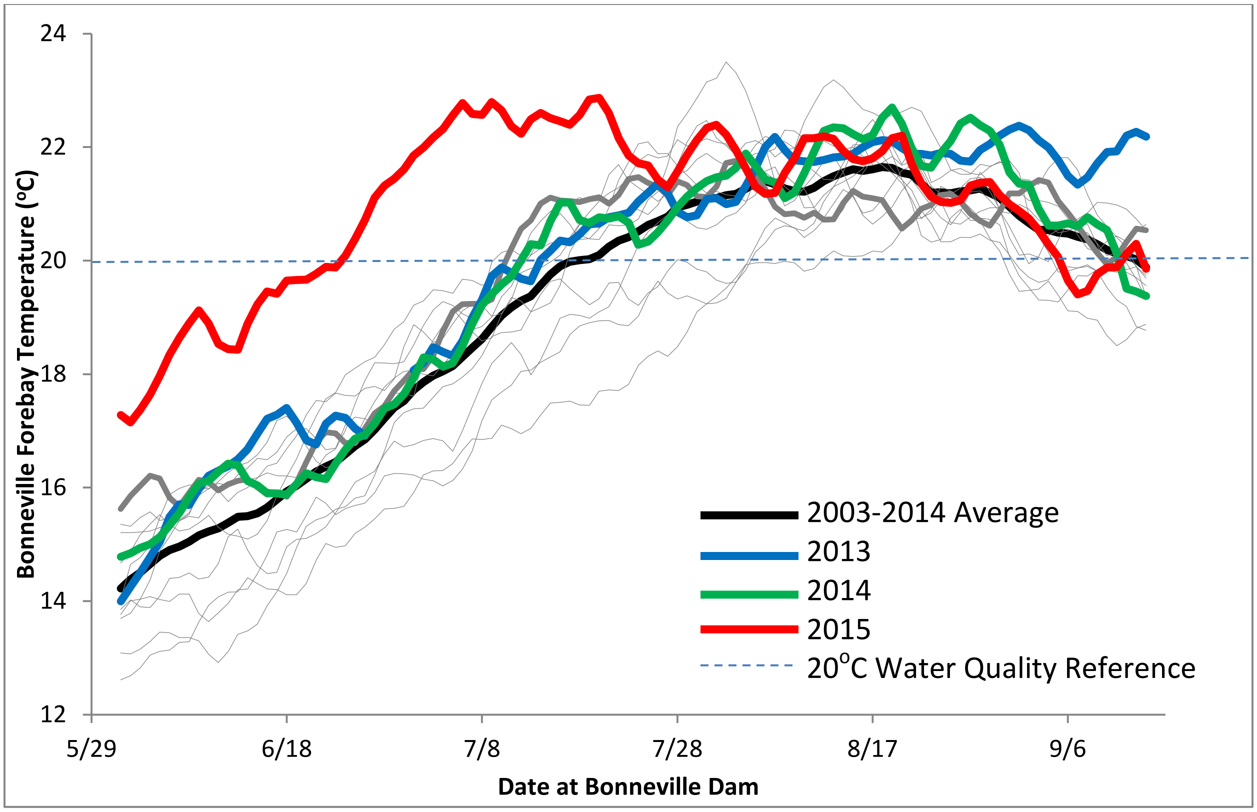

Figure 3: Daily average temperatures (°C) in the Bonneville Dam forebay from June 1 to September 15, 2003 – 2015.

Results

Travel Time and Temperature

To estimate travel times in the reach between Bonneville and McNary Dams, the period of time between the last detection at Bonneville and the first detection at McNary was calculated. It must be recognized that these travel times are somewhat biased, as only survivors are included in the analysis. Because the travel times of fish that perished are unknown, the calculated travel times are not completely representative of the entire run of steelhead that passed Bonneville Dam. To examine the patterns in travel times and their association with Bonneville forebay temperatures, we produced histograms of the Bonneville-to-McNary travel times, grouping individuals by the Bonneville forebay water temperatures at the time of their last detection at Bonneville Dam.

As temperatures in the Bonneville forebay increase, longer travel times are observed for both Snake River steelhead (Figure 4) and Upper Columbia steelhead (Figure 5). Travel times of 50 days or greater occur rarely for Snake River fish until Bonneville temperatures reach 19–20°C. Upper Columbia steelhead generally have shorter travel times, but show a similar trend in increasing travel times with increasing temperatures.

It is worth noting that individuals with longer travel times may be more susceptible to multiple sources of mortality, such as thermal stress, predation, and harvest (Keefer et al. 2009). However, it is critical to note that travel times reflect only the fish that successfully migrate through the entire reach, and do not describe the migration or mortality of fish not detected at McNary.

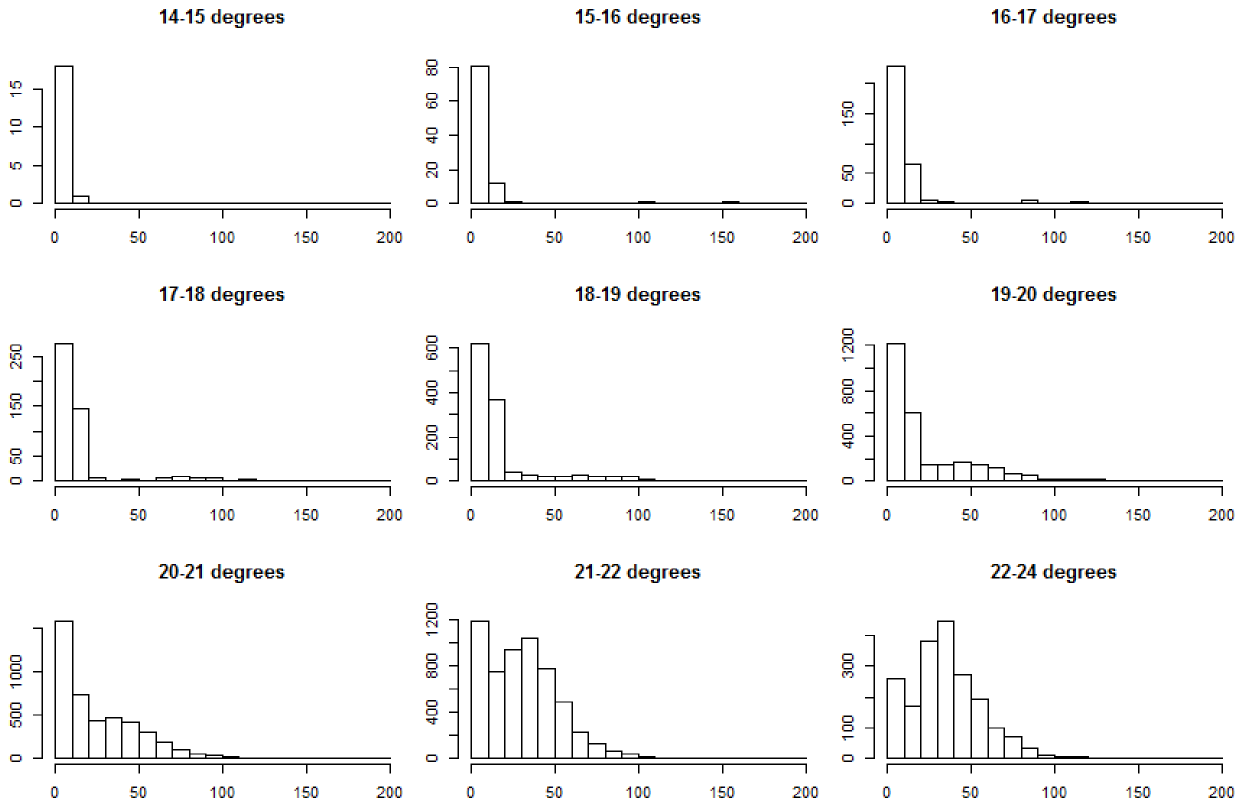

Figure 4. Histograms of travel time from Bonneville to McNary for Snake River PIT-tagged steelhead over various ranges of Bonneville forebay temperature..

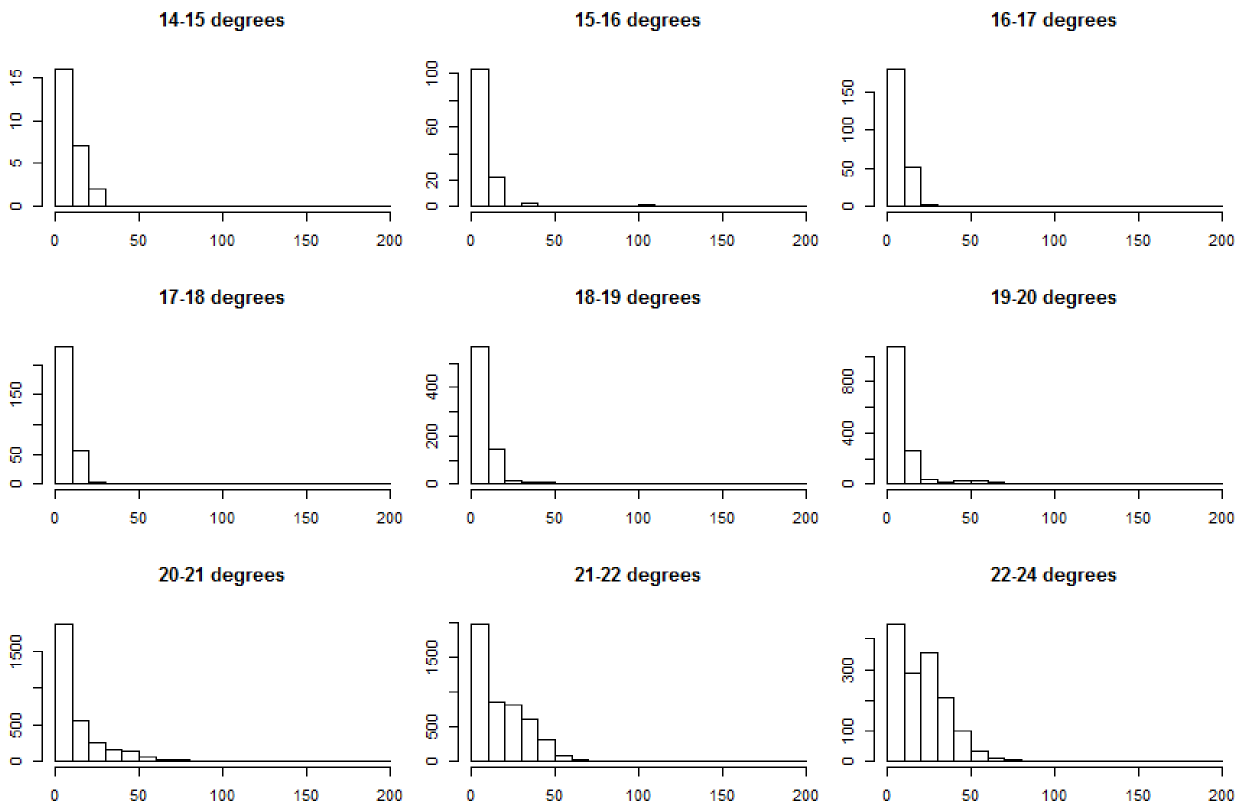

Figure 5. Histograms of travel time from Bonneville to McNary for Upper Columbia River PIT-tagged steelhead over various ranges of Bonneville forebay temperature.

Conversion Rate and Temperature

To assess the relationship between water temperature and steelhead conversion rate, we first employed a generalized additive model (GAM), which allowed a more flexible shape of conversion rate curve through a smoothing polynomial function. GAMs are particularly useful for modeling non-linear trends in ecological processes (Fewster et al. 2000), and here we used a GAM to assess a general trend in conversion rate under a range of water temperatures. Initial modeling used detection at McNary Dam as the response, and a range of explanatory variables including basin of origin, rear type, arrival date (Julian date), and Bonneville forebay temperature. The final GAM models, presented below, exclude basin of origin and rear type, as they did not contribute significantly to the models. For the smoothing function of the GAM, we utilized thin plate regression spline.

The results of GAM indicated that, in general, conversion rate increased with later arrival date, and decreased with rising water temperature (Figure 6). In more detail, conversion rates followed a constant trend until water temperature reached approximately 18°C, and a decreasing trend above 18°C.

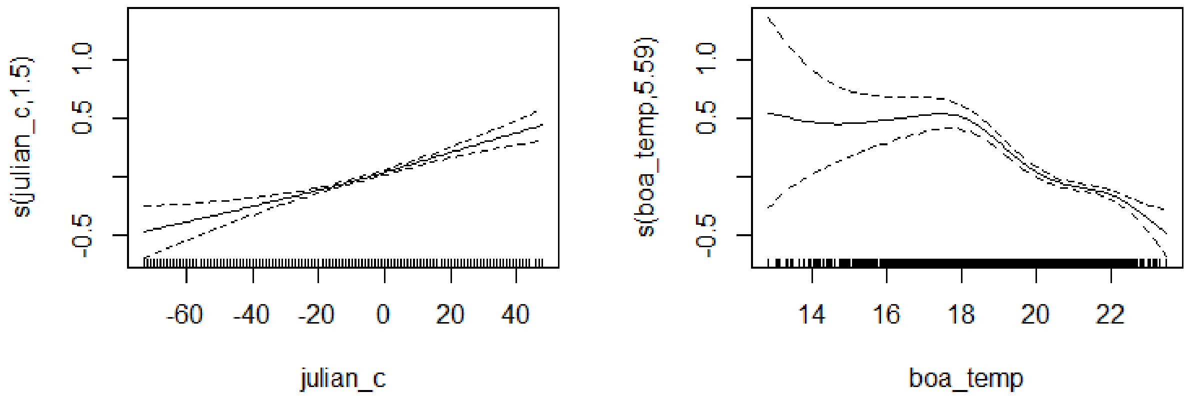

Figure 6. Smoothed trend lines for conversion rate vs. arrival date (as Julian day) (left pane) and conversion rate vs. Bonneville forebay temperature (right). Arrival date is centered on the peak migration time (mid-August). Dashed lines indicate uncertainties in the model. Y-axis is labelled s(cov,edf) where cov is the covariate name, and edf the estimated degrees of freedom of the smooth.

Subsequent to the GAM analysis, we fitted four logistic regression models to assess in more detail the relation between conversion rate and various other variables (Table 2). We first constructed two models: one with temperature + arrival date as the explanatory variables, the other with temperature + arrival date + rear type (wild or hatchery) + ESU (Snake or Upper Columbia) + rear type:ESU interaction as the explanatory variables. We then fitted two more models with the same explanatory variables as the first two, but allowed the new models to have separate slopes for below and above 18°C (i.e., piecewise models). The piecewise models were constructed based on the results from the GAM, which suggests an inflection point in conversion rates around 18^{o}C. We constructed all models with detection at McNary as the response variable.

As a rough rule of thumb, a difference in AIC value greater than 10 indicates a strong evidence of better fit for the model with a smaller AIC. When an informative explanatory variable was added to a model, we expected deviance to decrease by more than 1. Judging from the AIC values, both piecewise models had a better fit than their "single slope" counterparts. Models that included rear type and ESU had large enough decreases in deviance to be considered better models than the ones with temperature and arrival date only (Table 2). Despite differences in model fit, all four models indicated a significant negative relation between conversion rate and water temperature. Due to similar outcomes, we did not see the benefit of estimating separate conversion rate for each ESU and rear type (Figure 7b). Therefore, a piecewise model with explanatory variables temperature and arrival date ("Model 3" in Table 2) would offer the most straightforward interpretation of conversion rate vs. water temperature relationship (Figure 7a).

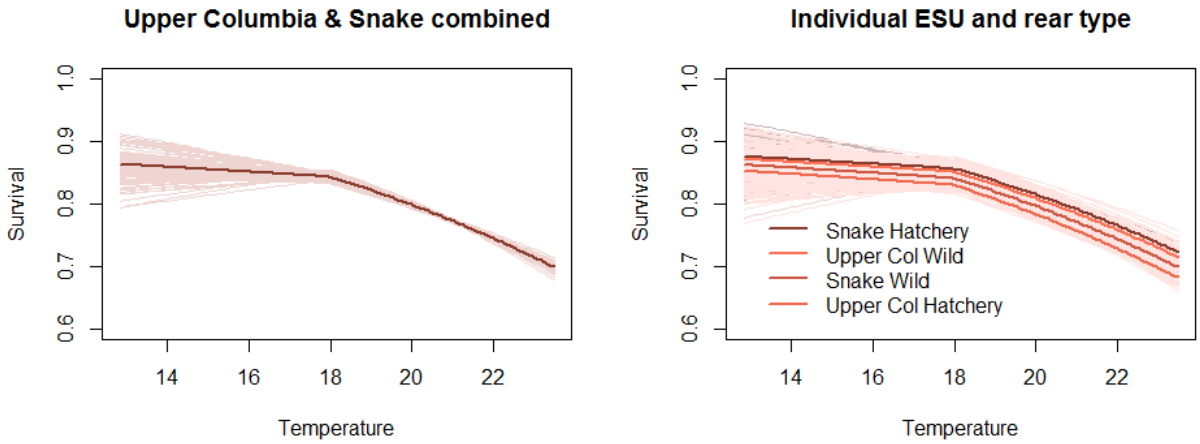

Figure 7: Conversion rate (i.e., survival) of combined ESU and rear types (left) and separate ESUs and rear types (right) over a range of forebay temperatures (°C) encountered by steelhead at Bonneville Dam during the peak migration season. The shaded areas indicate uncertainties of the models. Curves were developed from Model #3 (see Table 2 for details).

Our final model ("Model 3" in Table 2) suggested that conversion rate stayed nearly constant in water temperature below 18°C (p= 0.452) and in water temperature above 18°C, conversion rate showed a negative relationship with temperature (p< 0.001). Further, conversion rate increased with a later arrival date (p< 0.001), but this seasonal effect was negligible to overall conversion rate compared to temperature effect. For example, 1 day later in the season was associated with approximately 0.2% increase in conversion rate, while 1°C increase in temperature was associated with approximately 4% decrease in conversion rate.

Table 2: Four logistic regression models were fitted to assess the relationship between conversion rate and various variables. AIC values were used to assist the model selection. Although Model 4 was the most parsimonious, all models indicated a negative relation between conversion rate and temperature.

Model	Estimate	Standard Error	*z* value	Pr(>z)	AIC	Deviance	Degrees of Freedom
Model 1: Temperature + Julian Date					40,809	40,803	38,157
(Intercept)	1.638	0.033	50.123	0			
Temperature	-0.138	0.01	-13.719	0			
Arrival date	0.007	0.001	9.859	0			
Model 2: Temperature + Julian Date + Rear Type + ESU + Rear:ESU					40,768	40,756	38,154
(Intercept)	1.738	0.037	46.419	0			
Temperature	-0.135	0.01	-13.378	0			
Arrival date	0.007	0.001	9.4	0			
Wild	-0.116	0.033	-3.508	0			
Upper Col	-0.199	0.029	-6.752	0			
Wild:Upper Col	0.274	0.076	3.614	0			
Model 3: Model 1+ Piecewise Slope					40,804	40,796	38,156
(Intercept)	1.684	0.037	45.414	0			
Temp<18°C	-0.031	0.041	-0.752	0.452			
Temp>18°C	-0.153	0.012	-13.246	0			
Arrival date	0.007	0.001	9.239	0			
Model 4: Model 2+ Piecewise Slope					40,763	40,749	38,153
(Intercept)	1.783	0.041	43.027	0			
Temp<18°C	-0.033	0.041	-0.803	0.422			
Temp>18°C	-0.149	0.012	-12.87	0			
Arrival date	0.007	0.001	8.823	0			
Wild	-0.118	0.033	-3.574	0			
Upper Col	-0.197	0.029	-6.698	0			
Wild:Upper Col	0.276	0.076	3.639	0			

Model Fit

There were no major concerns for violation of model assumptions. Binned residual plots showed the constant variance assumption was adequately met (Figure 8).

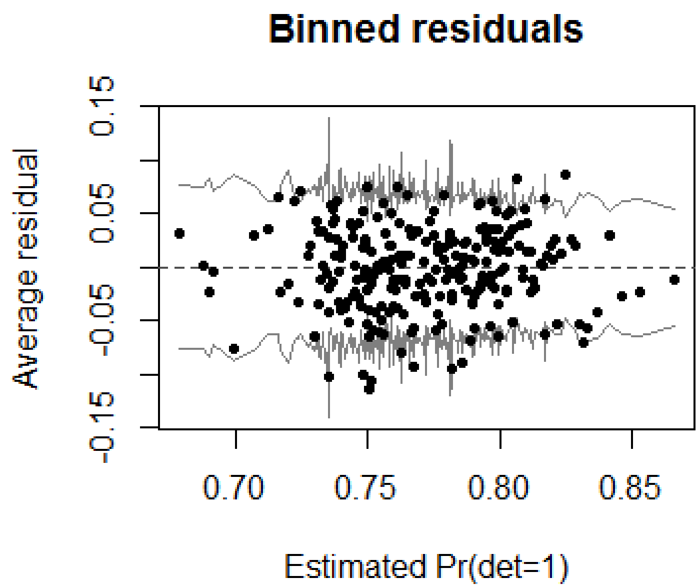

Figure 8. Binned residual plot for the final model (i.e., Model #3) had some outliers, but overall showed constant spread of residuals and no major concerns for violation of model assumptions.

Graphical representation of adult ladder counts and temperature at Bonneville Dam

At your request, we have compiled daily ladder counts of salmon and steelhead at Bonneville Dam for 2011-2015, along with daily temperatures from the Bonneville forebay (Figures 9 and 10). Bonneville forebay monitors are not installed or removed on the same dates every year, but are generally installed in March and removed in September. All available temperature data are presented. Please see the attached datasheet for the raw data. It is important to note that these data represent only observed passage, and are not indicative of environmental constraints that may have influenced fish passage.

The above analyses show a significant decrease in conversion rate for adults that pass Bonneville when temperatures are above 18°C. Table 3 shows the proportion of the fish counted that passed Bonneville dam when temperatures reached that threshold in each of the five years. Because monitors are removed before the end of the passage season, only the proportion of the run passing while temperature data are available are shown in Table 3.

Because the sockeye passage occurs over a short time span, almost the entire run can pass while temperatures are less than 18°C (as in 2011 and 2012), or while temperatures are greater than 18°C (as in 2015). The proportion of steelhead passing at temperatures above 18°C ranged from 62% to 99%. No spring Chinook passed at temperatures above 18°C. The proportion of summer Chinook passing at temperatures above 18°C ranged from 5% to 92%. In all five years, 100% of the fall Chinook run passed at temperatures above 18°C.

Table 3: Percentage of adults in each year that passed Bonneville Dam when forebay temperatures were higher than 18^{o}C while temperature data were available. The dates range of the table includes all available Bonneville forebay temperatures available for the given year. Spring Chinook pass Bonneville between March 1 and May 31. Summer Chinook pass Bonneville between June 1 and July 31. Fall Chinook pass Bonneville between August 1 and November 30.

	Year of Return				
Species	**2011**	**2012**	**2013**	**2014**	**2015**
Date Range	3/29-9/12	3/15-9/18	3/22-9/17	3/15-9/23	3/19-9/15
Spring Chinook	0.0	0.0	0.0	0.0	0.0
Summer Chinook	4.6	17.8	33.5	34.0	92.4
Fall Chinook	80.9	100.0	100.0	100.0	100.0
Steelhead	62.0	89.4	97.3	94.9	98.5
Sockeye	0.8	2.9	38.5	44.6	99.6

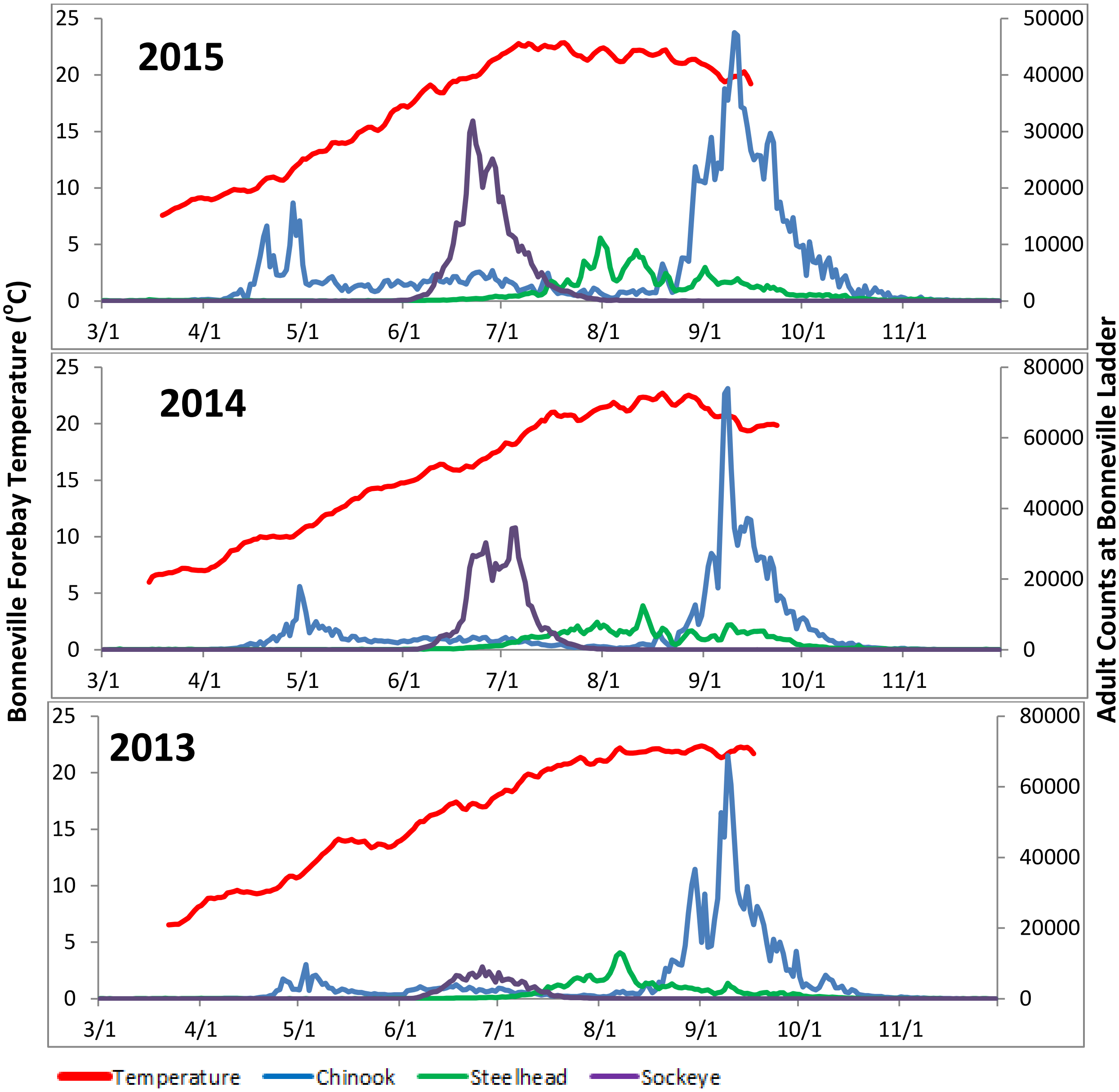

Figure 9: Adult ladder counts and Bonneville forebay temperatures for 2013 – 2015.

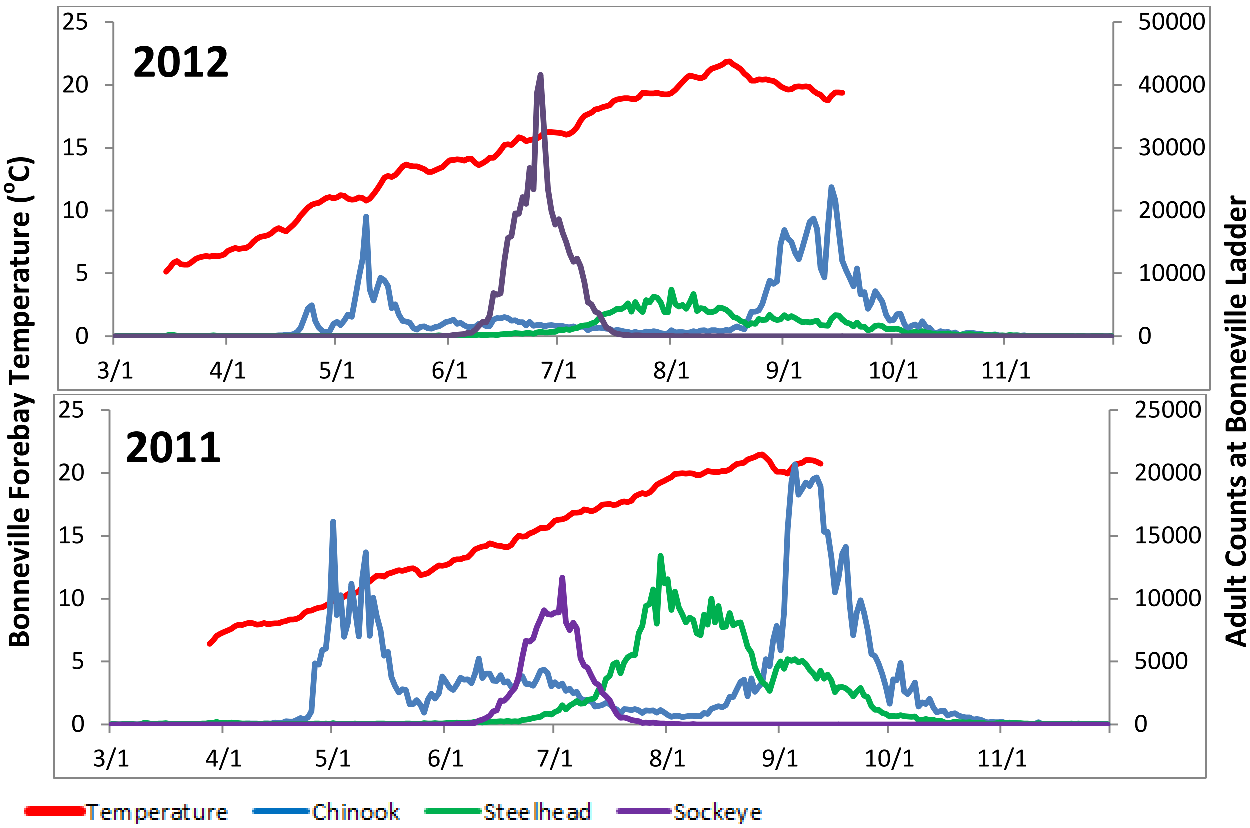

Figure 10: Adult ladder counts and Bonneville forebay temperatures in for 2011 – 2012.

Correlation Between Bonneville and McNary Forebay Temperatures

At your request, we have calculated the correlation between the Bonneville forebay and McNary forebay temperatures, with McNary temperatures lagged by 5-, 7-, and 9-days for 2011 – 2015. The date range of temperatures available for these years is presented in Table 3. Bonneville and McNary forebay temperatures are highly correlated (Table 4) in all years. However, forebay temperatures are measured only to the tenth of a degree Celsius, and temperatures do not vary widely over short time scales. Therefore, it is not surprising that Bonneville and McNary forebay temperatures should be highly correlated.

There are not large differences in the temperatures experienced between 5-, 7-, and 9-day migration times. However, while the 5-, 7-, and 9- day travel times requested were assumed for sockeye, spring Chinook, and fall Chinook for the years 2003 – 2015, median travel times for steelhead between Bonneville and McNary range from 9 – 30 days for Upper Columbia steelhead, and 12 – 40 days for Snake River adults that migrated in-river as juveniles. With extended travel times, estimating an average temperature experienced, or the total accumulation of thermal units experienced, becomes more difficult with temperature data from the dams (i.e., mainstem). If migrating steelhead spend time in thermal refuges prior to moving upstream, their travel times will be extended and mainstem temperatures will not reflect their temperature experience.

Table 4: Correlation coefficients between Bonneville and McNary forebay temperatures, with McNary temperatures lagged 5-, 7- and 9-days behind Bonneville temperatures. All coefficients are significant at the level of P<0.0001.

Return	Lag Period Between BON-MCN		
Year	5-day	7-day	9-day
2011	0.996	0.994	0.992
2012	0.992	0.988	0.986
2013	0.990	0.986	0.984
2014	0.992	0.989	0.986
2015	0.994	0.990	0.987

Harvest Management Data Sources

Columbia River fishery harvest is considered under the terms of a Federal Court order agreement, the 2008-2017 United States v. Oregon Management Agreement, finalized in May 2008. The terms of that agreement established a Technical Advisory Committee (TAC). The TAC is comprised of representatives of the states of Oregon, Washington, Idaho, the US Fish and Wildlife Service, NOAA Fisheries, the Bureau of Indian Affairs, the Warm Springs Tribe, the Umatilla Tribe, the Nez Perce Tribe, the Yakama Nation and the Shoshone-Bannock Tribes. Members of the TAC are required to be qualified fishery scientists with expertise in harvest management of Columbia River fish runs. TAC's primary responsibility is to develop, analyze, review data, develop reports, and develop recommendations regarding harvest management in the Columbia River. TAC also utilizes and exchanges data with the Pacific Salmon Commission, The North Pacific Fishery Management Council, the Pacific Fishery Management Council, and the United States section of the Pacific Salmon Commission as it pertains to Columbia River salmon stocks. TAC is responsible for the development of run size projections and compilation of catch and escapement data for the Columbia River.

Columbia River fisheries are actually implemented under the terms of the Columbia River Compact. The Columbia River Compact is charged by congressional and statutory authority to adopt seasons and rules for Columbia River commercial fisheries. In recent years, the Compact has consisted of delegates for the Oregon and Washington agency directors, acting on behalf of the Oregon Fish and Wildlife Commission (OFWC) and the Washington Fish and Wildlife Commission (WFWC). The Columbia River treaty tribes have authority to regulate treaty Indian fisheries.

When addressing commercial seasons for Columbia River fisheries, the Compact must consider the effect of the fishery on escapement, treaty rights, and the impact on species listed under the Endangered Species Act. Working together under the Compact, the states have the responsibility to address the allocation of limited resources between recreational, commercial, and treaty Indian fishers. This responsibility has become increasingly demanding in recent years. The states maintain a conservative management approach when considering Columbia River fisheries that will affect species listed under the ESA.

Annual run size projections, landings by fishery, escapement and harvest regulations for the Columbia River are published in annual joint staff reports. These data for 2015 are published in "2015 Joint Staff Report: Stock Status and Fisheries for Spring Chinook, Sockeye, Steelhead, and other Species, and Miscellaneous Regulations" by the Joint Columbia River Management Staff, Oregon Department of Fish and Wildlife and the Washington Department of Fish and Wildlife. Inquiries regarding harvest of Columbia River anadromous fish should be directed to Tucker Jones at the Oregon Department of Fish and Wildlife and Ron Roler at the Washington Department of Fish and Wildlife.

References

Fewster, RM., Buckland, ST., Siriwardena, GM., Baillie, SR., Wilson, JD. 2000. Analysis of population trends for farmland birds using generalized additive models. *Ecology*, 81(7):1970-1984.

Joint Columbia River Management Staff. 2015. 2015 Joint Staff Report: Stock status and fisheries for spring Chinook, summer Chinook, sockeye, steelhead, and other species, and Miscellaneous regulations. January 21, 2015.

Keefer ML, CC Caudill, CA Peery, SR Lee. 2008. Transporting juvenile salmonids around dams impairs adult migration. *Ecological Applications*. 18(8):1888-900

Keefer ML, CA Peery, B High. 2009. Behavioral thermoregulation and associated mortality trade-offs in migrating adult steelhead (*Oncorhynchus mykiss*): variability among sympatric populations. *Can. J. Fish Aquat. Sci.* 66:1734-1747

Keefer ML, TS Clabough, MA Jepson, CC Caudill, BJ Burke, KE Frick. 2015. Overwintering distribution and fallback behavior by adult radio-tagged steelhead in the federal Columbia River power system, migration years 2013-2014 and 2014-2015. Study Code ADS-P-13-2.

Keefer ML, C Caudill, T Clabough, K Collis, A Evans, C Fitzgerald, M Jepson, G Naughton, R O'Conner, Q Payton. 2016. Adult steelhead passage behaviors and survival in the federal Columbia River power system: Draft technical report. Prepared for the US Army Corps of Engineers.