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TECHNICAL MEMORANDUM

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To: Dennis Lynch, US Geological Survey

From: Noble Hendrix

Project: Evaluation of Dam Removal and Restoration of Anadromy (EDRRA) in the Klamath Basin, USA

Subject: Evaluation of long-term changes in Klamath Basin Chinook populations from dam removal and restoration of anadromy versus no action

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Introduction

Decision makers are often faced with having to make a decision without perfect information (Berger 2006, Hilborn and Walters 1992). Decision theory may facilitate this process by providing a framework for evaluating alternative decisions under uncertainty (Berger 2006). By uncertainty, we are most often referring to alternative states of nature (i.e., the set of conditions over which the decision maker has no control). For example, two states of nature concerning the chance of rain tomorrow are: 1) that it will rain tomorrow or 2) that it will not rain tomorrow. Alternative actions may then be evaluated in light of the uncertain state of nature. Returning to the rain example, assume that there are two possible actions being considered: 1) bring and umbrella and 2) do not bring an umbrella. One can then evaluate the two actions given the probability of rain obtained, say, via a weather forecast. Ultimately, the goal of being explicit about the uncertain states of nature and the actions is to make an informed decision. Here the states of nature were binary, but they may also be a much broader set of conditions that are not under the control of decision makers. In the context of fisheries management these may be biological rates such as the inherent productivity of a species or physical conditions such as variability in the environment. Here I analyze two alternative actions pertaining to a Chinook salmon

(*Oncorhynchus tshawytscha*) population in the Klamath Basin under uncertain states of nature. This analysis informs the determination by the Secretary of the Interior (Secretarial Determination) regarding the removal of four mainstem dams on the Klamath River (for more information, pleases see klamathrestoration.gov).

Both fall and spring run Chinook salmon existed in the Klamath Basin historically (Andersson 2003), and they used the full extent of the watershed including tributaries to Upper Klamath Lake (Fortune et al. 1966; Lane and Lane Associates 1981; Moyle 2002; Hamilton et al. 2005). The current upper bound to anadromy is Iron Gate Dam located 190 miles from the mouth of the Klamath River. In the tributaries of the Klamath Basin that currently have anadromy, the majority of Chinook runs are fall run, whereas spring run Chinook are found in the Salmon and Trinity rivers (Andersson 2003).

The two actions being evaluated are: 1) a Dams Removal Alternative (DRA) in which the four mainstem dams (Iron Gate, Copco I, Copco II, and J.C. Boyle) are assumed to be removed and 2) a No Action Alternative (NAA) in which the four mainstem dams remain in place.

To address the need to evaluate the DRA and NAA actions, I constructed a model, Evaluation of Dam Removal and Restoration of Anadromy (EDRRA), to forecast annual abundances of Chinook salmon in the Klamath Basin incorporating uncertain states of nature (Hendrix 2011). The main sources of uncertainty that defined the states of nature in EDRRA were: 1) the production of offspring by the spawning stock of Chinook salmon in the lower Klamath basin (Klamath River below Upper Klamath Lake), 2) the spawning capacity of the lower Klamath River below Iron Gate Dam, 3) the spawning capacity between Iron Gate Dam and Upper Klamath Lake (UKL), 4) the proportion of fall versus spring-run Chinook in the tributaries to UKL, 5) the production of offspring in the tributaries to UKL, 6) the importance of flow for affecting offspring survival, and 7) the importance of the Klamath River below the confluence with the Trinity and near-shore ocean conditions to offspring survival. For more information on EDRRA, please see Hendrix (2011).

The objectives of this technical memorandum are: 1) to provide brief descriptions of the two actions; 2) to provide a short description of the methods used to forecast the two actions over uncertain states of nature; 3) to define a metric for evaluating the relative performance of DRA versus NAA over specific time periods; and 4) to provide results of the performance metric over multiple states of nature.

Methods

No Action Alternative and Dam Removal Alternative Actions

The two alternative actions are different with respect to several components of the Klamath Basin. I briefly describe them here; however, additional information on the Secretarial Decision can be found at klamathrestoration.gov and additional information on how the two actions were modeled in EDRRA can be found in Hendrix (2011). The No Action Alternative was modeled in EDRRA with the following components:

- All Dams remain in place
- Hatchery production at Iron Gate and Trinity River Hatcheries remain at current levels
- No reintroduction of Chinook salmon to the tributaries of Upper Klamath Lake
- Hydrology in the Klamath River managed according to the NMFS 2010 Biological Opinion (NOAA Fisheries Service 2010)
- No restoration of tributaries to the Klamath River or tributaries to Upper Klamath Lake

The Dam Removal Alternative was modeled in EDRRA with the following components:

- Four mainstem dams removed in 2020
- Hatchery production at Iron Gate and Trinity River Hatcheries remain at current levels until 2028, after 2028 only Trinity River Hatchery remains in production
- Reintroduction of Chinook salmon to the tributaries of Upper Klamath Lake to meet capacity of the system in the year prior to dam removal and continuing for 10 years (2019 - 2028)
- Hydrology in the Klamath River managed according to KBRA
- Restoration of tributaries to the Klamath River including tributaries to Upper Klamath Lake as described in the KBRA

Production and harvest

The EDRRA model used the Ricker stock-recruitment model (Ricker 1975), where the offspring from year t (R_t) is the number of age 3 adults in the ocean and R_t is a function of spawners (S_t) in year t. The general Ricker stock recruitment function is:

$$R_t = \alpha S_t \exp\left(-\beta S_t\right) \qquad \text{(Equation 1)}$$

where α is the productivity of the equation and β is related to the spawner abundance that maximizes recruitment ($S_{max} = 1/\beta$) .

This general model can be log transformed to make a linear function:

$$\log(R_t) = \alpha' + \log(S_t) - \beta S_t \qquad \text{(Equation 2)}$$

where $\alpha' = \log(\alpha)$. Additional terms can be added to the model to reflect factors that explain additional variability in the stock-recruitment relationship. The general equation for the log Ricker stock-recruitment function that has additional factors is:

$$\log(R_t) = \alpha' + \log(S_t) - \beta S_t + \sum_{i=1}^{n} \theta_i X_{i,t} \qquad \text{(Equation 3)}$$

where θ_i is the parameter associated with factor *i* and $X_{i,t}$ is the value of factor *i* in year *t*.

For the lower Klamath Basin under NAA, a factor was added that reflected annual variability in the survival in the Klamath River below its confluence with the Trinity and into the nearshore ocean in year t (CVI_t)

$$\log(R_t) = \alpha' + \log(S_t) - \beta S_t + \delta CVI_t \qquad \text{(Equation 4)}$$

The equation for production in the lower basin under DRA after removing the mainstem dams in year 2020 was

$$\log(R_t) = \alpha'^{*} + \log(S_t) - \beta_{new} S_t + \delta CVI_t \qquad \text{(Equation 5)}$$

where the productivity term (α') in Equation 4 was modified to represent the effects of KBRA, and the productivity term was represented as α'^{*} in the DRA actions; and β_{new} was the parameter associated with additional capacity. Please see Hendrix (2011) for a description of the implementation of KBRA on the stock productivity parameter and the β_{new} parameter.

The equation for production in the tributaries to Upper Klamath Lake (UKL) used a form of the Ricker model that included the unfished equilibrium population size parameter ($E_{new,t}$) rather than β. This formulation was based on the formulation used in Liermann et al. (2010), which was used for defining parameter estimates in the tributaries to UKL as described in Hendrix (2011). The equation for the production in the tributaries to UKL was

$$R_{UKL,t} = S_{UKL,t} \exp\left\{\alpha_{UKL}{}^{*}\left(1 - \frac{S_t}{E_{new}}\right) + \delta CVI_t + \gamma_{IGH} Q_t\right\} \qquad \text{(Equation 6)}$$

where $R_{UKL,t}$ was the offspring from year t produced in Upper Klamath Lake tributaries; $\alpha_{UKL}{}^{*}$ was the productivity in the UKL tributaries, which was composed of both fall and spring-run Chinook and influenced by KBRA actions; E_{new} was the unfished equilibrium population size; Q_t was the Klamath River flow that had an impact on survival of offspring as determined by a survival to flow relationship of Iron Gate Hatchery (IGH) fish; and the magnitude of this effect was γ_{IGH}.

Hatchery production was also incorporated into EDRRA (Hendrix 2010). Survival of hatchery fish was estimated from a retrospective analysis of hatchery survival rates and flows in the Klamath and Trinity Rivers. Please see Hendrix (2011) for a description of how hatchery production was incorporated into EDRRA. Under the DRA action, hatchery production at IGH ceased in 2028, and this was the main difference between the DRA and NAA actions with respect to hatchery production.

The EDRRA model used an existing harvest model constructed by NMFS entitled the Klamath Harvest Rate Model (KHRM, Mohr et al. In Prep). The role of the KHRM is to determine the harvest given abundances of ocean ages 3, 4, and 5 from natural and hatchery sources. In each year, the total production (escapement in the absence of harvest) was calculated to determine if a fishery could operate. Depending upon the level of total production, a harvest rate was applied based upon a harvest rate control rule (F-control rule). Additional conservation constraints may also need to be satisfied before calculating the total allowable harvest, which was then apportioned among ocean commercial, ocean recreational, river, and tribal fisheries. The KHRM also included a maturation schedule, and it calculated the numbers in each age class that escaped to spawn. The escapement values were summed across ages to calculate the spawning abundance, which completed the life-cycle. For more information on how the KHRM was used in the EDRRA model, please see Hendrix (2011).

Metric for evaluating performance of DRA versus NAA

Although there was considerable uncertainty in the absolute estimates of Chinook abundance over the possible states of nature in both the NAA and DRA actions (Hendrix 2011), the decision to perform one action over another could still be assessed by analyzing relative performance. The EDRRA model used Monte Carlo simulation to integrate across multiple states of nature. Monte Carlo simulation makes multiple draws from probability distributions of all model parameters to construct parameter sets (in the case of EDRRA, there were 1000 parameter sets). Each parameter set represented a single state of nature. Thus for a given state of nature, the EDDRA model was run under NAA and the abundance of Chinook salmon in each year was saved. The values saved were: 1) total production (escapement in the absence of fishing); 2) Ocean commercial harvest, which had the same pattern as Ocean Recreational harvest so the Recreational was not saved; 3) River harvest; and 4) Tribal harvest. Using the same state of nature (parameter set), the EDRRA model was run under DRA, and the abundance of Chinook salmon in each year saved. The relative performance was computed across multiple states of nature by computing model results for each action, one state of nature at a time.

The parameter sets were not perfectly paired, and they differed in the productivity parameter for the lower Klamath basin (α'^{*}) due to the method by which KBRA effects were included under DRA. Thus, this parameter was not the same for the NAA run and the DRA run within the paired model runs. With the exception this productivity parameter, all other parameters were the same for a given state of nature.

There were two time periods over which the Chinook abundances were of interest. The first was the full time period of the model (2012 – 2061) and the second was the performance once the dams were removed (2021 – 2061). A metric (M) was developed that evaluated the performance of the DRA action relative to the NAA action for a single state of nature k via the following equation:

$$ {}^{k}M = \frac{\left(\sum_{t=j}^{T} {}^{k}N_t^{DRA} - \sum_{t=j}^{T} {}^{k}N_t^{NAA}\right)}{\sum_{t=j}^{T} {}^{k}N_t^{NAA}} * 100\% \qquad \text{(Equation 7)} $$

where ${}^{k}N_t^{DRA}$ was the abundance for state of nature $k = 1, \ldots, 1000$ in year t under action DRA and j indicated the starting year for the metric (j = 2012 for the full time series and j = 2021 for the post-dam removal time series), and T = 2061. Because the EDRRA model was run for 1000 states of nature, there were 1000 values of the metric M for each of the total production and the 3 harvest components. Statistics such as the mean, median, 2.5% and 97.5% were calculated on the 1000 M values. In addition, a statistic indicating the probability that DRA was greater than NAA was calculated by using an indicator function, in which all states of nature where ${}^{k}M > 0$ were given a value of 1 and all with ${}^{k}M \leq 0$ were given a value of 0. The sum of the indicator was divided by the total number (in this case 1000) to obtain an estimate of the probability that DRA > NAA for the time period specified.

Results and Discussion

Running the EDRRA model with paired DRA and NAA actions provided important information regarding the relative performance of the two actions over multi-year periods (Table 1). Because total production included both escapement and harvest, it was a good quantity for evaluating the performance of the two actions. While also useful, the harvest quantities were more sensitive to the harvest control rule and the allocation defined in KHRM.

The performance metric had lower values for the full time period than the post-dam removal period. For the 2012 – 2061 period, the median total production under DRA was 66% higher than NAA with a 95% interval of (-4%, 242%), whereas for the 2021-2061 period, the median total production under DRA was 80% higher than NAA with a 95% interval of (0%, 271%). Finally, the probability of higher Chinook production under DRA relative to NAA was 0.971 for 2012 – 2061, whereas it was 0.976 for 2021-2061.

The same general patterns were observed for the harvest metrics with higher relative abundances under DRA than NAA. Still, the mean, median, and 95% interval values were lower for the harvest quantities (Table 1). The probability of having higher harvests under DRA relative to NAA were also lower than for total production; the probability that DRA > NAA ranged from 0.9 to 0.95 for the full time series (2012-2061), whereas it ranged from 0.92 to 0.97 for the post-dam removal period. The harvest values were lower than the total production values likely due to states of nature in which there was either limited or no fishery in many years. Under these states of nature, there was enough production to maintain a population, but not enough to consistently support a fishery. Such states of nature would have had higher total production (escapement plus harvest) under the DRA action relative to the NAA action, whereas the harvest would have been equal or potentially zero for both DRA and NAA. These values were thus dependent to some degree upon the harvest control rule that was implemented (please see Hendrix 2011 for further information on the F-control rule used in EDRRA).

Table 1. Results of running a cumulative analysis of the Dam Removal Alternative with KBRA actions (DRA) versus the No Action Alternative (NAA). The first four values in the table represent statistics related to the percentage increases in the abundance under DRA relative to NAA ([DRA – NAA]/NAA * 100%), whereas the last statistic quantifies the probability that abundance under DRA is greater than NAA.

Period	Statistics	Total Production	Ocean Harvest	River Harvest	Tribal Harvest
2012-2061	Mean	78%	46%	31%	50%
	Median	66%	36%	26%	38%
	2.5%	-4%	-15%	-3%	-14%
	97.5%	242%	181%	110%	197%
	Pr(DRA>NAA)	0.971	0.901	0.947	0.908
2021-2061	Mean	92%	54%	37%	58%
	Median	80%	42%	31%	45%
	2.5%	0%	-14%	-1%	-13%
	97.5%	271%	209%	120%	227%
	Pr(DRA>NAA)	0.976	0.918	0.97	0.926

The probability of having higher total production under DRA relative to NAA was previously calculated as 0.75 for annual comparisons of DRA versus NAA (Hendrix 2011). In Hendrix (2011) the relative performance of DRA versus NAA was calculated on annual abundances across multiple states of nature, whereas the abundances were summed over multiple years and across multiple states of nature here. This difference has important implications for the calculation of the relative performance of DRA versus NAA. If each year was independent, the results from Hendrix (2011) could be used to determine the probability of having higher abundances under DRA versus NAA in some number of years by using a Binomial distribution with parameters N = 50 and p = 0.75. A similar calculation could be applied for the post-dam removal years. However, the years are *not* independent due to offspring of a particular brood year returning at multiple ages and annual correlation among environmental covariates included in the EDRRA model (e.g., flows). As a result, the calculations presented here were useful for understanding how the DRA action performed relative to the NAA action over the full 50 years of forecasts and the post-dam removal period.

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